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Hydrographic applications of the global positioning system

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

HYDROGRAPHIC APPLICATIONS OF THE
GLOBAL POSITIONING SYSTEM

by

Penny D. Dunn

and

John W. Rees, II

September 1980

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Hydrographic Applications of the
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September 1980

ABSTRACT

Global positioning satellite have been tested under a variety of conditions and have demonstrated exceptional accuracy. The most portable of the Phase I development equipment is the manpack/vehicle user equipment (MVUE or Manpack). The purpose of this study was to determine if a manpack is suitably accurate for coastal hydrographic surveying at scales on the order of 1:20,000. The MVUE was placed aboard the Naval Postgraduate School Research Vessel (R/V) ACANIA and operated under survey conditions in Monterey Bay, California. This objective required the testing of the manpack developed by Texas Instruments, Inc., under varying survey conditions to determine the degradation of positional accuracy. The limit of the survey scale to which the unprocessed manpack data could be employed in a real-time operation was found to be 1:80,000 and smaller by the positioning error criteria of 0.5 mm to the scale of the survey [Umbach, 1976]. Application of differential techniques during the post-processing of the MVUE position data increased the limit of the survey scale to 1:40,000 using the same positioning criteria.

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I. INTRODUCTION

The NAVSTAR Global Positioning System (GPS) is designed to be the most advanced three-dimensional navigation and positioning system in the world in terms of accuracy, coverage, and availability to all potential users. Phase I, the Full Scale Engineering Developing, has begun with Phase II Field Testing presently planned for 1982-83. The system is planned to be fully operational in 1987 [Jorgensen, 1980].

As part of Phase I, a number of tests were conducted to determine how well the system performed under simulated operating conditions. While GPS is also to be made available for commercial users, the testing emphasis has been in the area of high positional and navigation accuracy as applied to military usage. The operating conditions simulated were military exercises, i.e., beach landings, bombing runs, or ship navigation in narrow channels.

One item of importance to any military operation is an accurate map or hydrographic chart. Accurate positioning is vital to the production of an accurate chart. This is an application of GPS that has not been addressed by the user community. Accurate positioning for mapping and charting has long been a problem, especially for charting,

since it involves a platform moving in a random manner on the water. The accuracy standards for hydrographic surveying have been established by the National Ocean Survey (NOS). The standards allow an rms positional error of 1.5 mm at the scale of the survey of which approximately 0.5 mm is positioning error [Umbach, 1976]. This amounts to 5 m of positioning error for a 1:10,000 survey scale, 10 m for 1:20,000, etc. The Texas Instruments (TI) Manpack/Vehicular User Equipment (MVUE) was tested in a simulated hydrographic operation to determine position accuracy and, therefore, the survey scale to which the MVUE is applicable.

Hydrographic operations will benefit from the implementation of the NAVSTAR GPS in several ways: positional accuracy; continuous, worldwide, all weather availability; simplifcation of survey operations; and cost reduction [NAVAIDS, 1980].

At present, the Naval Oceanographic Office obtains its position accuracy for coastal operations by the use of short and medium range navigation aids. Deep ocean navigation and positioning accuracy is dependent upon a combination of long range electronic positioning, doppler satellite navigation, and a inertial navigation system which requires a sophisticated computer backup. A navigation system not limited by range would be a great asset [CNOC, 1979].

The Defense Mapping Agency (DMA) and the Naval Oceanographic Office (NAVOCEANO) are both interested in satellite positioning as it applies to mapping and charting [NAVOCEANO, 1979]. The purpose of this thesis is to supply information to these and other interested government agencies and potential commercial users concerning the application of one type of receiver, and to make recommendations concerning future tests and applications [CNO, 1980].

II. SATELLITE POSITIONING

A. STATE OF THE ART

Satellite navigation and positioning has been possible for two decades. With the launching of Transit/NNSS (Navy Navigation Satellite System) satellites in 1960, worldwide satellite navigation became a reality. For the first time, surface and subsurface ships had a reliable, all-weather, passive system that would allow the computation of latitude and longitude to an accuracy of 0.185 km (0.1 nm) [McDonald, 1979].

The Transit system is divided into three parts: satellites, tracking systems, and user receivers and computers. The system requires a minimum of four satellites in polar orbits at an altitude of 1075 km (600 nm). The satellites transmit on two frequencies: 150 MHz and 400 NHz. By measuring the Doppler shift, which is a unique function of the user's position and motion relative to the known satellite orbit, it is possible to determine one's position. It is important to have an accurate method of determining one's own velocity in order to solve the position equations. If the motion is not known accurately, additional position fix error will result.

Ground stations track each satellite and measure and update emphemeris and time synchronization data. A central station controls system tracking and provides a data injection facility, a central computer, and communications center. The user equipment is available to both the military and civilian community. The commercial equipment consists of a low cost, single channel receiver, a small digital computer, a navigation program, and an operator's control/display terminal. The military version has a dual channel receiver and is usually tied into a sophisticated integrated navigation system.

The Transit system works best in midlatitudes. Near the equator, the orbits are spaced far apart and the user must wait a considerable time (average 100 minutes) for a position fix. Since the receiver antenna does not handle signals well that come in from high elevation angles, position computation in high latitudes is chancy. There have been several proposals to eliminate the problem, i.e., more satellites, coded signals, and more orbits including an equatorial orbit. These proposals would help eliminate the long waiting period between satellites and shorten the time interval needed to determine position (average 5-20 minutes). They do not solve the problem of sensitivity between position error and uncertainty in user velocity. Position solution still requires a complex data processing

procedure and it only provides a two-dimensional position [McDonald, 1979].

B. NAVSTAR

1. Applications

The NAVSTAR (Navigation Satellite Time and Ranging) System enables an order of magnitude reduction in positioning error. It will provide the user with three-dimensional information (Appendix A): three-dimensional position (latitude, longitude, altitude); three-dimensional velocity (North-South, East-West, Up-Down), and precise time. Most of the medium and long range positioning and/or navigation aids on the market today have been developed to meet general navigation requirements and often have limited survey applications. A system unaffected by variable ground conductivity or signal loss would greatly improve the planning, preparation, and conduct of survey operations worldwide. If its accuracy meets the survey requirements, NAVSTAR may replace some of the short range systems as well. It will be usable by both the military and civilian community with the degree of accuracy presently impossible.

Merchant vessels will be able to navigate port-to-port using the NAVSTAR GPS as their primary navigation tool. GPS could not only allow them to operate in an economical manner but also navigate in congested waters with a greater degree of safety. It could make sea-traffic

control feasible which is important in heavily trafficked, narrow straits, i.e., the English Channel and the Straits of Hormuz, and is especially important as oil tankers become larger and more unwieldy.

It may possibly be used for air-traffic control. It has been proposed that the system could allow narrower flight path separation and greater traffic density at terminals. Of particular value would be use for collision avoidance and the routing of aircraft over the most economical routes [McDonald, 1979].

GPS has been proposed for air search and rescue. The oil companies may have a use for GPS for positioning of floating drilling platforms. A substantial portion of their research money goes to development of positioning systems. In the area of research, it can be used as a time distribution system for radio astronomy, for direct measurement of ionospheric group delay (a function of the system's two frequencies), and as a very precise geodetic positioning technique [Parkinson, 1978].

2. System Description

The NAVSTAR GPS is also divided into three parts: space, ground, and user. The space segment originally called for 24 satellites; three orbits (120° apart) with 8 satellites at an altitude of 20,183 km (10,898 nmi) evenly spaced in each 12 hour orbit (Fig. 1). This

configuration provided for multiple satellite visibility and the best geometry for position determination. It also provided for worldwide, full-time, instantaneous availability [McDonald, 1979]. Due to budget considerations, the number of satellites has been reduced to 18 [Jorgenson, 1980].

The position solution requires either four satellites visible or three satellites visible and a known user altitude. Both solutions require "good" relative satellite geometry in order to determine position. If the needed number of satellites are not in view or the geometry is poor, a system failure occurs.

It was originally assumed that distributing the six remaining satellites regularly (60° apart) about the orbit (uniform constellation) would be satisfactory. However, subsequent evaluation of that configuration indicated that other orbit configurations would be better. The three orbit configurations to be discussed are the uniform constellation, the nonuniform constellation, and the rosette constellation.

The original system description called for the orbits to be at angles of 63° with the equitorial crossings 120° of longitude apart. For the uniform and nonuniform constellation configurations, it was found that a longitudinal different of 55° was better as it allows the three orbit planes to be mutually perpendicular. The three

orbits then divide the earth's sphere into eight equal octants, each octant being an equilateral spherical triangle.

The uniform constellation configuration distributes the satellites equally about the orbit, 60° apart, the relative phasing of the satellites from one orbit plane to the next is zero; i.e., when the ground trace of a satellite in one orbit is crossing the equator, satellites in the other two orbit planes are also crossing the equator. This property insures that the maximum distance between the satellites occurs at the equator.

The difficulty with the uniform constellation is that for mid-latitude users only two of the three orbits are visible, and in order to acquire four satellites, the user must wait until two satellites are visible in each orbit. This is because the satellites are 60° apart. At some point in time, the four satellites will assume a symmetrical arrangement. When this occurs, all four satellites are in the same plane and the navigation solution is indeterminate. This condition constitutes an outage of the system.

With 18 satellites in a uniform constellation, this problem occurs 72 times per day in the northern hemisphere and 72 times per day in the southern for a total of 144 outages a day in the midlatitudes. This problem also occurs in the polar regions. Twelve times

a day in each region, an observer would have six satellites visible where all six are in a common plane. Therefore, a total of 168 periods of no solution occur per day with the worst case locations suffering loss for up to a half hour.

Various forms of the nonuniform 18 satellites constellation have been investigated, all using six satellites in each orbit plane. The best appears to be one that is modelled on the original 24 satellite constellation but with two adjacent satellites removed from each orbit plane. The original relative phasing of 24 satellites was selected so that ground tracks were common for sets of three satellites (one from each orbit plane) resulting in eight ground tracks. The six satellites removed from the original configuration were selected to eliminate two ground tracks, leaving six.

Outages still occur as a result of poor geometry but they have been reduced to six per day in each hemisphere. They affect, unfortunately, the midlatitudes but only two longitude regions. The outage areas are separated by 180° of longitude and are mirror images of each other. These outage areas should be placed in locations that have the least impact on users.

It has been suggested by Jorgenson, 1980, that these areas be located over the North Atlantic and Pacific areas. The outages would occur in each area three times a day for a maximum of 40 minutes each time. In the southern

hemisphere the areas affected are in the Western Indian Ocean and Eastern South Pacific. While placing the outage areas in these locations would not seriously affect navigation for most users, it may limit military and hydrographic uses.

The rosette constellation consists of 18 separate orbit planes as viewed from the North Pole. The longitude spacing is 20° between orbits. The relative phasing of the orientation of the satellites is again designed to minimize outages such that when a satellite crosses the equator in one place, in the adjacent orbit plane, the satellite is 40° ahead of the equator, in the next 80°, etc. Computer simulation (modeling) has shown the rosette constellation to be the best. The only problem involves placing and maintaining the satellites in their orbits. This is important because replacement was to be done by the Space Shuttle which would launch more than one satellite at a time. Therefore, a "modified" rosette has been proposed: a 24 satellite rosette with six orbits missing. Replacement is easier and geometry is almost as good as the nonuniform constellation.

The navigation signal is transmitted from the satellite on two RF frequencies: L_1 at 1575.42 MHz and L_2 at 1227.6 MHz. The L_1 signal is modulated with both the P-code (Precision) and the C/A (Clear Access or

Coarse Acquisition) pseudo-random noise codes in phase quadrature. The L_2 signal is modulated with the P-code only. Both L_1 and L_2 signals are modulated with the navigation data-bit stream at 50 bps. The codes serve two functions: (1) identification of satellites as each has a unique code pattern and (2) measure of navigation signal transit time by measuring the phase shift necessary to match codes.

The P-code, a long, pseudo-noise, precision code generated by each satellite, is unique to each satellite and repeats itself once every seven days. It is extremely difficult to acquire the signal unless the ground receiver knows which time-slice in the seven day code to search. It is much easier to match the C/A code and lock on.

The C/A code, which repeats itself every milli-second, is a short, pseudo-noise code also unique to each satellite. It is relatively easy to match and lock onto since the search time is so short. The C/A code is normally acquired first and transfer is made to the P-code by a handover work (HQW) contained in the navigation message. The receiver generated P-code is shifted in phase to synchronize with the incoming P-code when triggered by the HOW. The total phase shift required for lock on is a measure of pseudo-range time which includes user clock offsets, propagation delays, and system errors.

The navigation message from the satellite contains all the data that the user's receiver requires to solve for a position. It includes information on the status of the satellite, time synchronization information for transfer from C/A to P-code, parameters for computing clock correction, the ephemeris of the satellite, and corrections for signal propagation delays. It also contains almanac information and status of the other satellites. A detailed description of the navigation message will not be given here other than saying it is formatted in five subframes of six seconds each for a total data frame of 30 seconds [Milliken, et al, 1978].

Errors in pseudo-range measurements associated with the satellites come from several sources. They are space vehicle clock errors, atmospheric delays, group delays, ephemeris errors, multipath, receiver noise and resolution and unresolved receiver vehicle dynamics. The magnitude of the residual uncorrected errors is summarized in Table I. The satellite vehicle (SV) clock errors and ephemeric errors are generally considered together since the SV clock error is very small and can appear to be a component of ephemeris error which is the difference between actual satellite position and calculated position. Atmospheric delays result from (1) refraction in the ionosphere which is a function of frequency and (2) tropospheric errors due to elevation

angles. Group delays result from processing and passage of the signal through the SV equipment and are generally measured during ground tests of the equipment. Multipath errors occur as a result of signal reception from more than one propagation path distorting the data. Receiver noise and resolution errors occur in signal processing and are attributable to inaccuracies in the estimation of vehicle dynamics. This error is compensated for by receiver design and by Kalman processing of signals. No allowance is made for high dynamics of the vehicle itself [Milliken, et al, 1978].

The ground Control Segment (CS) tracks the satellites to determine ephemeris and clock error. These are then used in models to predict ephemeris and clock error for each satellite. This information is transmitted (uploaded) to the satellite and passed on to the user as part of the navigation message.

The Control Segment consists of four Monitor Stations (MS), an Upload Station (ULS), and a Master Control Station (MCS). The Monitor Stations are located at Hawaii; Elmerdorf AFB, Alaska; Guam; and Vandenburg AFB, California. The MS are unmanned data collection centers and are under the control of the MCS. The MS measures pseudo-range (sum of actual range displacements plus the offset due to user timer error) with respect to a cesium clock and meteorological

data to determine atmospheric delay corrections. The data is processed at the MS and relayed to the MCS on demand.

The ULS and the MCS are both located at Vandenburg AFB. The ULS uploads data to the satellite on receipt of a control word. The data can be user navigation information, diagnostics, or commands to change satellite time. The MCS performs computations necessary to determine ephemeris and clock errors, generates upload information for the ULS, and maintain a record of satellite status and the contents of the navigation processor. During Phase I testing, the satellites will be uploaded at least once a day [Russell, et al, 1978].

The user segment at present consists of the Phase I development equipment of which there are four types: X-set, Y-set, Z-set, and the manpack (Manpack/Vehicle User Equipment). The X-set is a high vehicle dynamic, four channel, dual frequency system that acquires all four channels simultaneously. This provides the user with a real-time instantaneous position. The Y-set is a single channel, dual frequency system that is sequential. Position update is a function of the time it takes to cycle through the channels. The Z-set is a single channel, single frequency set that is also sequential. This set is the commercial prototype model and is not as accurate as the X-set and Y-set. The manpack is similar to the Y-set but its

reduced size also reduces the flexibility of electronic processing hardware and software it can contain and, therefore, reduces its accuracy.

III. HYDROGRAPHIC TEST PROCEDURES AND PERFORMANCE

A. INTRODUCTION

The purpose of this test was to determine the scale at which the MVUE satellite receiver could be successfully used as the primary positioning system for a hydrographic survey. "The indicated repeatability of a fix (accuracy of location referred to shore control) in the operating area, whether observed by visual or electronic methods, combined with the plotting error, shall seldom exceed 1.5 mm (0.05 in) at the scale of the survey" [Umbach, 1976]. Of the 1.5 mm, approximately 0.5 mm is reserved for positional error [Umbach, 1976]. For simplicity, "seldom" will be taken to mean less than 10 percent of the time [Munson, 1977] and the 1.5 mm value will be interpreted as a 90 percent accuracy level. Table II shows the relation of this value to various survey scales.

To establish the repeatability of the MVUE satellite receiver with respect to the shore, a relative comparison with known geodetic points was required. Since both a static and dynamic (shipboard) comparison were needed, the geodetic stations had to be selected in the proximity of the dynamic operation (Fig. 2).

1. Static Comparison

To detect drift in the satellite derived position, the MVUE antenna was placed over a second order goedetic mark, USE MONUMENT, established by the Corps of Engineers. This mark was located 600 m south of the dynamic test area on a sand dune adjacent to Del Monte Beach, 250 m from the water line (Appendix B). No first order station was known to exist within or near the test area.

2. Dynamic Comparison

To control shipboard position information relative to the shore, the Motorola Mini Ranger III (MRS III) short range position fixing system was employed. A system description is given in Appendix C. The MRS III was selected because it was part of the navigation equipment aboard the dynamic test platform, R/V ACANIA.

Positions were obtained using trilateration software programmed into the MRS III Data Processor (Fig. 3). Range measurements (to the nearest meter) from the ship to two third order USGS geodetic shore stations (Appendix B) were converted into two-dimensional positions corresponding to the Universal Transverse Mercator (UTM) coordinate system (northing and easting) (Fig. 4). In addition to UTM positions, range information was recorded in order to check the MRS III position solution and to apply calibration corrections to the UTS positions during post-processing.

An automatic data recording system was used to store the time, event number, and UTM position (northing and easting) on magnetic tape and to record the time, event number, and ranges on a paper printer.

Depths were recorded on a Raytheon Model DE-731 Recording Fathometer during the dynamic tests to provide a relative topographic check at points where the ship's track crossed over the same point. Tide data from the Monterey, California, tide station (#941-3450) was used to reduce the recorded depths to a relative scale (Fig. 5). The topography of the test area is a smooth, gentle sloping (east to west, 10 m/km), sand and mud bottom with depths ranging from 30 m to 825 m.

3. Calibration

The MRS III was calibrated before and after the actual field testing of the MVUE receiver to establish a reference for determining system drift, remote antenna height dependency, repeatability, and range correctors. Four geodetic stations (Monterey Bay 4 (MB4), USE MONUMENT, SEASIDE, and MUSSEL) were selected as calibration sites. One additional calibration site, NAIL (on the pier adjacent to the R/V ACANIA), was used. NAIL was surveyed to third order accuracy by members of the test party. The MRS III control station (receiver/transmitter) was set over the surveyed position, NAIL, while the two MRS III reference stations (code 1 and code 4) were individually

placed over each of the geodetic marks (Fig. 6). The measured baseline distances, recorded to tenths at two-second intervals for one to two minutes, were compared against inverse computations between the four pairs. The four baselines varied in range from 1800 m to 4700 m. As an additional check, a Tellurometer MRA 5 (Appendix D) was used to measure the same ranges. The Raytheon depth recorder was not calibrated, since only a relative depth was needed to check track crossing points.

B. MRS III AND GPS COORDINATE FORMAT

Mini Ranger III (MRS III) data were collected in Universal Transverse Mercator (UTM) coordinates and manpack data in geographic coordinates (GP). The MRS III data processor read two range rates (in meters) and output either the direct range data or converted the ranges into X,Y coordinates transformed to correspond with WGS-72 related UTM values. The manpack could output data in UTM and GP. The UTM output, however, was in military UTM format which uses zones and bands. Special MVUE data recording equipment was unavailable. Data from the manpack was recorded manually. During the pre-operational test period conducted to familiarize test personnel with the procedures, the military UTM format was a source of confusion. The UTM meter values changed rapidly when the ship is in motion; therefore, it was simpler to record data in WGS-72 geographic coordinates.

C. EQUIPMENT INSTALLATION TESTS

The tests conducted were divided into three categories: equipment installation tests, performance evaluation tests, and survey operation simulations. The plan for the GPS/ Hydrographic Applications Test is found in Appendix E.

1. Visual Inspection

A visual inspection was performed every time the MRS III and the manpack were set up. Set up involved connecting all antenna cables, interface connections, antenna mountings, and equipment mountings according to the equipment specifications. Shore station batteries were checked to verify that they were fully charged.

2. Power Stability

The power stability test was conducted onboard the test vessel to measure voltage, ripple, and stability. The power was found to be extremely stable. The test vessel was the R/V ACANIA, the Naval Postgraduate School (NPS) oceanographic research vessel. This ship is equipped with the necessary hardware to regulate the power to specifications set by Texas Instruments (TI). The only additional equipment used was a regulated power supply to step down the ship's voltage to the 24 volts required by the manpack.

3. Operational Check

The operational check of the manpack was conducted every night during the test period. This required that

normal startup be accomplished, the Control Display Unit (CDU) be operating properly, and the test functions be performed with the required results. The manpack was turned on and allowed 15 minutes to warm up. The necessary information was entered through the CDU: initial time, estimated altitude, best estimate of position. Also entered at this time were waypoint (reference point) data (eight positions in WGS-72 latitude and longitude) which allowed the taking of range and bearing. No problems were encountered at any time during any of the pre-operational testing periods.

4. Truth Check

The truth check was used to determine the accuracy of the Mini Ranger III Positioning Determining System (MRS III). It was conducted once to determine MRS III range correctors. The MRS III transmitting antenna was removed from the ship's mast and set up on the pier over a re-surveyed (third order) position. Two MRS III transponders were set up over preselected geodetic positions. The location of these transponders was entered into the MRS III Data Processor using X,Y positions in meters (UTM format) with respect to the reference point on the pier. The distance from the transponders to the reference point was computed prior to this test using both inverse computations and Tellurometer measurements.

5. <u>Static Technical Performance</u>

The static technical performance test was a simple checklist of all the manpack operating functions. It was performed every night before data collection was begun. No problems were encountered throughout the testing period.

D. PERFORMANCE EVALUATION TESTS

1. <u>Beach Test</u>

The Beach Test was conducted for two nights; the first at the beginning of the test period, the second at the end. Observations were made to determine how well the manpack static readouts compared to the latitude and longitude of a known control point. The antenna of the manpack was placed directly above a second order control point and latitude and longitude readings were taken every 30 seconds for a period of several hours.

The satellite data were taken before and after the satellite ephemeris update. The elapsed time since update makes a great difference in the recorded values. Data taken before the update shows a mean offset value (difference between station position and GPS position) of 147.3 m with a standard deviation of 15.3 m. A plot of the first night of static data showed all the data points biased to the NW of the control station; the mean offset was 36.25 m with a standard deviation of 9.82 m (Fig. 7). A plot of the last night of static data showed the points distributed

fairly uniformly about the station (Fig. 8). The mean offset was 7.43 m and the standard deviation was 3.23 m. The difference between the two sets of data appears to be a result of operating the manpack in the dynamic mode the first night and the static mode the last. When in the dynamic mode, the manpack assumes a velicity of 25 m/s [TI, 1979]. It is assumed that the bias introduced the first night was a direct result of operating in a dynamic mode.

2. Pier Test

One night of testing was spent with the ACANIA tied up at the pier in order to determine how well the manpack operated in low-dynamic conditions (Figs. 9, 10). Local wave and wind action on the ship's hull and superstructure combined to swing the mast through an arc of several meters. The manpack antenna was mounted on the mast on the MRS III antenna support. This eliminated the problem of computing an offset distance between the two antennae. Two line-of-sight MRS III transponder reference stations were operated simultaneously. The MRS III positions provided a measure of how far the mast swung. The only disadvantage was that the MRS III measured ranges in whole meters only. The manpack positions were taken every 15 seconds for the duration of satellite availability. (The timing is a function of the receiver. the TI manpack waits 4.5 seconds after the

fix button is pushed to display a position. The display stays lit for 10 seconds. Therefore, 15 seconds is the minimum time between fixes.)

The data collected before and after ephemeris again showed a wide variation. The data overall, however, showed discrepancies larger than were expected. Prior to update, the mean offset was 1018.86 m with a standard deviation of 85.81 m. After update, the mean offset was 87.04 m with a standard deviation of 12.78 m. It is believed these discrepancies are the result of weak signals.

When the tests were first discussed, it was desirable that all the equipment be placed in a central location, the ACANIA's dry lab. This required running 15 m of coaxial cable having no greater than 3dB line loss. Texas Instruments was unsure whether or not the receiver would function with that long a cable. (They believed the antenna preamp would not drive the signal for that length.) An optimum of three meter length cable was recommended. The 25 m length was tried to determine if it were critical. During the course of data collection, a large number of weak signals were received. After that night of testing, the manpack was removed from the dry lab to the chart room aft of the bridge. This shortened the cable length to 5 m which, while not entirely eliminating the problem, cut the frequency of its occurrence significantly.

3. Anchor Test

The anchor test also occupied an entire night and was conducted to determine how well the manpack operated under moderately dynamic conditions. The MRS III transponder stations were operated as in the pier test. The manpack receiver was moved to the chart room and the antenna cable shortened; otherwise, it was operated as before. The R/V ACANIA was taken out to deep water, anchored, and the ship allowed to swing freely. The manpack positions were taken every 15 seconds for the duration of satellite availability.

Most of the data collection occurred before all the updates to the satellites had taken place. While the mean offset was 149.16 m with a standard deviation of 95.29 m, an overview of the data shows an improvement in the offset values from 520.9 m to less than 35 m in an hour. Unfortunately, satellite acquisition was lost after two hours on this occasion.

E. SURVEY OPERATION SIMULATIONS

1. High Dynamic Test

The high dynamic test simulates acceleration normally experienced during inshore surveying. This test was designed to determine whether loss or degradation of the manpack signal would affect position accuracy in a high speed turn. If the signal were lost, reacquisition time would become critical; if degradation were to occur position error would

be critical. Night operations and the use of vessel larger than hydrographic launch (120 feet vs. 30 feet) precluded running onshore lines and turns. Instead, it was decided to run a line at maximum speed (9 knots), make a 180° turn (Williamson), and return on the original track. The MRS III was again used for control.

Two tracks were run; one in a north-south direction, and one in an east-west direction (Figs. 13, 14). The north-south track was run before satellite update. The mean offset was 315.7 m with a standard deviation of 19.79 m. Only three satellites were available. The east-west line was run after satellite update but the positions recorded were worse than pre-update values. The mean offset value was 1002.16 m with a standard deviation of 149.22 m. The line was started with only two acquired satellites and one signal was lost as the line progressed. It is assumed that the bad values were the result of satellite signal loss.

2. <u>Survey Scenarios</u>

The survey scenarios involved three separate survey stimulations: a circle test, a 5 knot series of track lines, and two 9 knot track lines.

a. Circle Test

The circle test was conducted to determine how much radial error, if any, was introduced into the manpack position values. Two circles were run at a speed of 9 knots;

one in a clockwise, the other in a counterclockwise direction (Figs. 15, 16).

The first line was run in a counterclockwise direction before the satellites were updated. The mean offset distance was 31.10 meters with a standard deviation of 13.81 m. The second line was run in a clockwise direction after the update. The mean offset distance was 18.31 m with a standard deviation of 9.09 m. A visual comparison of the two circle plots shows no radial displacement between the MRS III values and the GPS, and none is indicated by the statistics. Both lines were run with four satellites.

At the completion of the circle test, it was decided to run a few 9 knot lines. Five available satellites were acquired. NAVSTAR Two (PRN 7) has a bad cesium standard which gave erroneous range values. Using this satellite's information in the solution of the position equations generally results in positions that have considerable error. The offsets increased from approximately 300 m to greater than 70,000 m. For this reason, this satellite was eliminated from future testing.

b. Nine-Knot Lines

Two nine-knot lines were run because that speed closest approached normal survey speed. Unfortunately, both lines were run before satellite update, and these data display the typical deterioration in position characteristic

of satellite ranges at the end of the 24-hour satellite data. Mean offset for the two lines was approximately 109 meters with a standard deviation of 6 m (Figs. 17, 18).

c. Five-Knot Lines

Two lattices were run at 5 knots. The first consisted of six lines: two north-south lines, two east-west lines, and two diagonals. The second set also consisted of six lines: three running NW-SE and three running NE-SW (Figs. 19, 20). Both lattices were designed so that line crossings could be evaluated for both position and depth. As in other tests, lines run before update showed very poor mean offset values and standard deviations. However, for the nine lines run after the update, the statistical results are very good. The average of the mean offset values comes to 38.01 m and a 10.84 m standard deviation. Visual inspection of the track lines indicates that offset between the MRS III and GPS values shows a north and east shift in GPS positions.

IV. ERROR ANALYSIS

To provide better control for comparing the NVUE satellite position to the MRS III position values, various error sources affecting geodetic positioning and the position accuracy of the MRS III system were explored. Errors which can occur fall into three categories: human error, random errors, and systematic errors. Human errors result from misreading instruments, transposing figures, faulty computations, etc. This type of error was of particular significance when considering the MVUE data which was manually recorded. These errors were usually large and were removed through the use of an edit program developed for this problem. The MRS III data was recorded automatically but still required the same editing because the data had to be transferred manually from paper copy to punched cards. Random errors are those which cannot be eliminated from the data. These errors result from accidental and unknown causes and include instrument errors, operator errors, observational errors, and ephemeral propagation anomalies. Systematic errors include built-in instrument bias, observer bias, faulty instruments, or factors such as temperature or humidity changes which affect the performance of measuring instruments. Some of

these errors are often manifested in a pattern which can be recognized; therefore, they can usually be removed. For those systematic errors which cannot be modelled, calibration will often produce estimations of the unresolved errors.

A. GEODETIC CONTROL

The first source of error involves the accuracy of the geodetic control points. Geodetic accuracy is usually given by the relative accuracy between geodetic control points. Errors in the measurement of azimuths, angles, and lengths affect the accuracy of geodetic points. The errors inherent in these control points are further propagated into the hydrographic positions.

The relative accuracy between control points for the third order class II geodetic stations is 1:5000 (Appendix B). For two stations (LUCES and MB 4), separated by 7715.5 meters, a station error of 7715.5 m divided by 5000 or 1.54 m exists. This translated into a 0.4 m change in position offset, that is, shifting the coordinates of one station by 1.54 m altered MRS III positions determined by trilateration so that a small change occurred in the distance (offset) between new MRS III position and the MVUE position.

B. COORDINATE TRANSFORMATION

Geodetic positions selected for MRS III shore sites were surveyed on the North American Datum 1927 (NAD-27).

The MVUE satellite data was recorded on the World Geodetic System 1972 (WGS-72). The MRS III derived positions were computed in the UTM coordinate system as discussed earlier.

All stations were converted from NAD 27 to WGS 72 using the adridged Molodenskiy formula. Two third order Doppler stations (Pt. Pinos 10277 and Monterey 10211) [DMA, 1976], within 1 km of Luces Point, were selected to compare the standard Molodenskiy Conversion Formulas, used by DMA-HTC to convert the NWL-9D (earth centered) surveyed positions of the Doppler stations to WGS-72 positions, with the abridged Molodenskiy derived positions. The average position difference was 9.9 m at an azimuth of 306° 02' 40.79" from south. When converted to UTM values, the mean northing and easting shift for the two stations was +5.73 m and -8.07 m respectively (Table III).

It was assumed that the datum shifts provided by the abridged Molodenskiy formulas were adequate and any major discrepancies would be identified as systematic and removed in post-processing by coordinate shifts.

To compare the MRS III data with the MVUE data required, the transformation of WGS-72 ellipsoid positions to the plane UTM coordinated system. Initial UTM reference station coordinates used in the MRS III Data Processor for trilateration computations were provided by DMA-HTC. To process the large volume of satellite data from WGS-72 to

UTM, it was necessary to use the U.S. Geological Survey (USGS) computer program J380, Coordinate Conversion [USGS, 1977]. This was due to the incompatability of the DMA-HTC software with the IBM 360/67 mainframe computer at the Naval Postgraduate School. A check between DMA values and the USGS program showed an average -0.034 m and +0.011 m shift in northing and easting. Since the significant part of this value is two orders of magnitude smaller than the 1 m resolution of the MRS III system, it will be assumed that the computer values from the two sources are virtually the same.

Variation of the baseline distance between two positions occurs when calculated by the inverse method (Sodano) on the ellipsoid (WGS-72) and when computed using the pythagorean theorem on the plane (UTM). Differences between the two computations were found to change linearly from 0.01 m at 30 m to 2.2 m at 8000 m (Fig. 21). Position comparisons between MRS III and MVUE values at distances less than 100 m would have less than an 0.02 m effect on the overall error. Most of the positions were separated by less than 100 m, and therefore, the bias is negligible.

C. GEOMETRIC DILUTION OF PRECISION AND REPEATABILITY

"For range errors of a given magnitude the relative geometry configuration between user receiver and unknown reference stations used for the navigation fix determined

the magnitude of position errors. The accuracy with which one can determine position is related to the range measurement accuracy by factors known as Geometric Dilution of Precision (GDOP)" [Djork, 1979]. Because testing was limited to the x-y plane, the Horizontal Dilution of Precision (HDOP), which is the two-dimensional aspect of GDOP, will be addressed. HDOP is a dimensionless gain coefficient which yields the horizontal position uncertainty when multiplied by the rms radial range error. The two MRS III reference stations were located such that the maximum error magnification (HDOP) due to geometry was 1.8 (Appendix G).

Two d_{rms} or 95% reliability diagrams for the MRS III shore station configurations are shown in Figures 22 and 23 for ranges with a standard deviation range error, 1σ, of 2 m. Repeatability is defined as the measure of the accuracy with which the system permits the user to return to a position as defined only in terms of the coordinate peculiar to that system [Bowditch, 1977]. The diagrams indicate that within each contour, 95 percent of the lines of position should not be displaced with the arithmetic mean of the position in any direction by more than the contour value. The formula used to compute the reliability contours was:

$$2\ d_{rms} = \frac{1}{\sin\beta}\left[(2\sigma_1)^2 + (2\sigma_2)^2\right]^{\frac{1}{2}} ,$$

where: $2\ d_{rms}$ = 8, 10, 12 m position error or 95% reliability

$\left.\begin{array}{ll}\sigma_1 & \text{standard deviation of each} \\ \sigma_2 & \text{range line of position (rms range error)}\end{array}\right\}$

$\sigma_1 = \sigma_2 = 2m$ for the MRS III system

D. MRS III POSITION AND RANGE ERRORS

Two independent methods were employed to evaluate the MRS III derived positions. In both cases, recorded MRS III range data was used to calculate the user position from two known reference stations in the UTM plane coordinate system.

Eighteen range pairs taken at one minute intervals from day 121 line 6 were used in the first method. The range values and known reference station coordinates (UTM) were entered into a computer program, UCOMP, developed by LCDR A. Pickrell, NOAA, to obtain geodetic positions and x-y values from range-range hydrographic operations. The mean difference for both northing and easting values was 0.8 m.

The second method is found in the computations used to determine the Horizontal Dilution of Precision in Appendix G. Four range pairs for positions at the limits of the survey area were selected for position computation by the least square technique. One position (#21099) was off by 17 m easting and 84 m northing. This is believed to be a result of signal losses encountered at that time while in

a Williamson turn. The mean difference for the remaining three stations is 1.8 m northing and 1.6 m easting.

The differences from both methods translates into less than a 0.5 m position offset change.

The listed probable range error for the basic MRS III positioning system is $\pm$ 2 m [Motorola, Inc., 1979]. This figure has been verified in three independent studies, one by the Systems Test and Evaluation Branch of the National Oceanic and Atmospheric Administration (NOAA) in September, 1977 [NOS, 1977], one by the Canadian Hydrographic Service in September 1973 [Munson, 1977], and the other under the direction of a joint USAF/Navy project at the Yuma Proving Ground Inverted Ranger in October, 1978 [Bjork, 1979].

Test results from the NOAA study indicated standard deviations of 1.2 m and less at vessel speeds less than 7.8 m/s (15 knots) (Fig. 24), for the basic MRS III range values. The Canadian study noted a RSS range error of 1.5 m for distances of 4 to 9 km. At Yuma, statistical comparison of the MRS III range measurements with laser truth data generated ranges supporting Motorola's claim of a one meter system for the MRS III for static and dynamic environments (to 20 m/s) [Bjork, 1979].

From pre and post calibration data for this project, range values for the two reference stations showed an increasing deviation from 0.14 m at 1800 m to 0.95 m

at 4700 m (Table IV). The 2 m value will be used in any computations requiring the range data.

Range correctors for each transponder were obtained by subtracting the mean measured calibration ranges from the computed inverse ranges, then averaging the four differences. Figure 25 is a plot of the range differences versus the inverse distance. Since most operating ranges exceeded 2000 m, it will be assumed that the relationship between range difference (measure-computed range) and the inverse distance is linear with little change (0.08 m/km) for increased separation between the control and reference stations. Though the accuracy of the data is insufficient to confirm this assumption, the trend is present and can be extrapolated from the test results in the NOAA study (Fig. 24) which noted: "Also evident is the independence of the error with regard to range (distance); in fact, linear regression of each of the lines produced error slopes of less than 0.003 m/km" [NOS, 1977].

Based on Figure 25, the final range corrections applied to the two remote stations, code 1 and code 4, were 5 m and 4 m respectively.

E. METEOROLOGICAL EFFECTS

"On its path an electromagnet ray passes through air of varying density. This causes bending of the ray due to refraction. It is a function of the refraction index of

of the air at all the points along the ray path. The refractive index depends on temperature, pressure, humidity, and other compositional elements of the atmosphere (dust, carbon-dioxide, etc.). Since these quantities cannot be measured along the entire ray, it is customary to generalize by taking the average wet and dry bulb temperature and pressure at both ends of the path" [Ghosh, 1979]. Resulting corrections to ray path distances can be obtained with meteorological parameters (temperature and pressure) through nomographs or in related equations. To establish the magnitude of the corrections, meteorological data was recorded and applied to Tellurometer measurements.

Refraction correctors determined for the Tellurometer MRA5 varied linearly from 0.02 m to 0.06 m at ranges of 1500 m to 4700 m respectively. Given the small order of magnitude for the Tellurometer correction and the fact that daily meteorological conditions in the operation area did not vary significantly, $2^{o}C$ and 15 mb, it will be assumed that the range differences will not vary substantially to affect the 1 m resolution of the MRS III system.

F. STATION ELEVATION

Errors associated with differences in reference transponder elevation (52 m maximum at MB 4) produce range differences of less than 0.1 m for the area when computed in the UTM coordinate system (Fig. 26).

G. MULTIPATH INTERFERENCE AND RANGE HOLES

"Multipath refers to the various paths an electromagnetic signal may follow prior to reception. These paths can be direct or reflected from the water's surface or some other object (Fig. 27). The effective signal at the receiver will be a composite signal whose strength depends on the strength and phase relationships of the direct and reflected signals at the receiver" [Gilb, 1976].

For low angle reflection from the water surface, the reflected and direct signals arrive at the receiver with nearly equal strength. The difference in phase at the receiver is caused by the direct and reflected signals traveling slightly different distances to the receiver thereby arriving at different times, and by phase changes of the reflected signal at the reflection points. For the small reflection angles associated with this test, the phase change occurring at the reflection point is close to 180°. Assuming a constant phase change at the reflection point, the relative phase of the two signals at the receiver will be a function of the extra distance traveled by the reflected signal.

"Destructive interference will occur when the path length difference between the direct and reflected paths is a multiple of the system's wave length" [Gilb, 1976]. Signal loss, or range hole, occurs when the signal received

is reduced below the sensitivity of the system. Appendix H contains the range hole computations and graph for the MRS III system. From the graph, range holes were expected at ranges in the vicinity of 4750 m and 6300 m. It should be noted that the shore reference points and their height above the water's surface will vary with the tide elevation. This causes the range holes to move as the tide changes. During testing, signal loss occurred several hundred meters to either side of the approximate range hole values.

At ranges and station elevations where the reflected signal reinforces the direct signal, the system range is increased. The use of only two reference stations eliminated the possibility of detecting bad MRS III positions based on multipath range values. The bimodal distribution of the offset vector (MRS III to MVUE position) (see Appendix I) seemed to suggest a possible multipath indication; however, these distributions were present in the Beach and Pier tests. For the Beach test, only the geodetic station positions were used and for the Pier test one standard deviation for both the northing and easting values was 1 m or less over a range of 5 to 8 m. This suggests that the source of the bimodal distribution is in the satellite navigation solution. The extended MVUE antenna cable (15 m) was considered as the source, but the original 3 m cable was used during the Beach tests and produced similar results.

The multipath problem will be placed in the random error category and not addressed further than to assume that the multipath ranges will have a negligible weighting effect on the statistical processing of the MRS III and MVUE position differences.

H. TIMING

During the MRS III system check prior to actual testing, it was noticed that from the time an event mark was manually requested, via the MRS III teletype console, until the event was displayed, a period of one second elapsed. The delay appeared to be the result of a brief pause in the MRS III system immediately after the event command. The most likely causes of this time difference are human response delay and the operational characteristics of the MRS III system.

At survey speeds of 5 and 9 knots, one second translates into a 2.6 m and 4.6 m displacement along the ship's track. The difficulty in applying this correction to the offset vector was that the azimuth angle between the offset varied in its relation to the track line (10° to 180°) from line to line for each day. This azimuth was found to be dependent on the specific satellites being interrogated. Consecutive lines using the same satellites for the position solution displayed a preferred offset azimuth. When a satellite was lost or a new satellite gained, the offset azimuth immediately shifted to a new direction (Fig. 28).

Due to the continuous change in available satellites, each group of track lines derived from the same satellite set would have to be addressed individually for time related offset corrections because of the azimuth change. It should be noted that the preferred offset direction for track lines occurring from time 0700 to 0845 is 133°. This corresponds to an average azimuth offset of 134° computed from the dynamic mode MVUE position data for the first Beach test, day 121. Offset values for track lines run after 0830 show a preferred azimuth of 254°. Unfortunately, no shore data was collected after 0845.

I. MVUE SATELLITE POSITION ERRORS

The sources of error for the satellite system were reviewed in Table I. Information providing numerical error values (CEP) was limited to the estimated position error (EPE) provided by the MVUE manpack upon request [CID, 1975]. Table V is a list of the maximum and minimum EPE values read from the manpack. These values were recorded at five minute intervals during the various tests. No strong correlation was found between these values and any of the offset standard deviations.

J. ANTENNA MOTION

During the Pier test, day 122, the MRS III UTM position was found to oscillate with the ship's roll. Two meters was

the extent of the variation associated with this period. Similar results occurred for the Anchor test, day 123.

K. TOTAL ERROR BUDGET

Of the error sources mentioned, the factors which noticeably alter the MRS III and MVUE position difference are the NAD-27 to WGS-72 datum transformation, the horizontal dilution of precision, and the calibration corrections for the MRS III ranges. Table VI contains a series of computations which compare offset vectors (distance and azimuth) from MVUE positions to positions derived from:

1. Original MRS III range data
2. Original MRS III range data plus range corrections
3. Original MRS III range data using shifted reference stations based on Doppler stations comparison
4. Original MRS III range data plus the range corrections using shifted reference stations.

Each successive comparison shows a slight offset decrease from the original data. In Case Two a 3 m position enhancement resulted from the application of the range correctors. A significant improvement was expected for Case Four since the shift represented range corrections and a full coordinate transformation based on satellite data. However, only an 8 meter decrease in offset was achieved.

It is reasonable to conclude that the coordinate shift is acceptable in the vicinity of Luces (within 1 km of both Doppler stations), but possibly not as effective when applied to the other stations, which are much further from the Doppler stations. The offset vector (10 m, 306^{o} azimuth from south) used to shift each geodetic control station was the average from the two Doppler stations located within 0.5 km of one another.

Based on static mode MVUE position data from the first Beach test, day 128, an average (post-update) offset vector of 7 m with a 3 m standard deviation and 313^{o} azimuth from south was obtained. This implies that the average Doppler offset applied to reference station MB 4 is probably close to the true shift for the station; therefore, the subsequent MRS III positions derived from the shifted reference positions are assumed accurate.

Applying the horizontal dilution of precision (HDOP) to the offset vector would result in a 4 m decrease when applied along the offset vector.

Table VII shows the various sources and the expected position improvement (decrease in offset between MRS III and MVUE data) when each is removed from the system. If all errors were removed to reduce the offset, an advantage of 6.4 to 7.8 m would result. This would reduce a typical track line offset vector with a magnitude of 37 m $\pm$ 12 m to 29 to 31 m $\pm$ 12 m. The remaining 31 m is too large to

be accounted for within the geodetic and MRS III error budget; therefore, it will be assumed to be a function of the satellite derived position.

Surveys of 1:80,000 (40 m position error) and smaller would be adequately covered under the 31 m $\pm$ 12 m conditions [Table II].

The change of the offset azimuth (MRS III to MVUE from south) from one track line to the next has proven too variable to apply a single vector correction for the entire survey period; however, for the time 0700 to 0830 when the average offset magnitude of 36 m and azimuth of 134° for the first night's Beach test, day 121, is applied to MVUE data from that period, it is apparent that a differential mode of operation is the most probable solution to the large offset problem.

Removal of the 36 m average offset value of day 121 from the 37 m average of the better tracks for the entire study reduces the MVUE performance relative to the MRS III configuration to an offset variation of 1 m with the 12 m standard deviation. This meets the 1:30,000 scale position error of 15 m from the 0.5 mm criteria.

The 3 m position improvement (offset decrease) from application of the range corrections to the original MRS III data for day 126, line 6 in Appendix 5 is another factor which will further improve the overall results

along with the differential values when it is removed from the data. Since the magnitude of the large correction value will vary from trackline to trackline, like the timing problem, a single value cannot be used for all lines. The important point is that in the final analysis, the systematic errors can be removed by differential applications leaving only the standard deviation as the system error.

V. GENERAL OBSERVATIONS

A. MRS III

1. Range Error

Range errors are commonly considered independent of distances within the range limit of the system, i.e., flat or nearly flat error slope (measured-computed range difference/known distance on the order of 0.003 m/km). The error slope determined from the calibration data was 0.08 m/km, indicating some dependence on range. This could indicate some equipment problems or, more likely, the absence of sufficient calibration sites at greater distances to adequately define this value.

2. Timing

For the low speeds at which this test was conducted, less than 9 knots, the along-track displacement due to the 1 second delay experienced with the MRS III system alters the error by 1.2 m. This could account for the 1 m offset difference between the average offset values of the tracks (37 m + 12 m) compared to the average beach value (36 m + 12 m). At higher speeds, timing would become an increasingly important factor.

3. Range Variation

An indication of the day to night variation of the MRS III range can be noted from Table VIII. These values represent averaged positions and ranges for the R/V ACANIA tied at the pier on which station NAIL is located. These values are close enough to allow the assumption that any day to night position difference will not greatly alter the statistical results of the data.

B. GPS

1. Satellite Availability

Only five satellites were available for the test period. These were satellites with Pseudo Random Noise Codes #4, 5, 6, 7, and 8. Each satellite was updated daily. During operations, various subset combinations of the five satellites were used to determine the position solution. Satellite #7 was found to be unstable and created large position errors when used in the solution. Whenever it became likely that this satellite had been interrogated, commands were entered into the CDU to suppress further use of the satellite.

2. Dynamic vs. Static MVUE Operation

The offset vectors for the dynamic and static operation of the MVUE during the Beach tests for day 121 and 128 displayed a distinct difference in the position solution. Relative to the geodetic station, the two

vectors were directly opposing and their difference, 29 m, could possibly be related to the 25 m/s velocity factor [Texas Instruments, Inc., 1979] used in the dynamic mode Fig. 29). Assuming that the direction of the velocity factor was in the opposing direction with a magnitude of 25 m, a 4 m position difference with a ± 10 m variation would exist. The extra 4 m might be resolved with a more sophisticated averaging technique or, possibly, the change in the ephemeris update between day 121 and 128 could account for the difference.

The same situation can be applied to the shipboard operations for the tracks which were selected for statistical analysis. In this case, the averaged total error value from Table VII, 7 m, is removed from the 37 m ± 12 m offset vector. A 5 m + 12 m position difference remains when the 25 m velocity factor is removed.

The values are too coincidental not to be dependent in some manner; however, due to lack of information regarding the velocity factor, no further speculation is warranted.

3. Preferred Azimuth

The offset direction (azimuth of MRS III to MVUE position from south) for the various satellite sets was found to be fairly consistent between days 121, 126, and 127. Due to the limited duration of the test, it is difficult to determine whether this indicates a preferred

direction. However, various problems encountered during the remaining days preclude ruling out this possibility.

4. Two Satellite Positions

Though the data collected in the high dynamic test on day 124 was insufficiently accurate for hydrographic applications, it was found that the satellite solution during a turn could be satisfied with only two satellites and still maintain a fair relative positioning when compared to the MRS III data. For the position solutions using three and four satellites, the resulting track lines showed exceptional correlation to the MRS III positions when the offset vectors were removed from each line.

5. Truncation of Input Data

During the last Beach test, day 128, six waypoints (geodetic positions) were entered into the MVUE receiver in WGS-72. Table IX contains a comparison of the values entered and those values returned upon interrogation. Since the values differ by as much as 0.2 seconds in latitude and longitude, the resulting offset vector leads one to speculate as to whether the position solution is also affected by this trend.

C. DEPTHS

1. Crossing Points

At satellite track line crossing points, soundings agreed within 3 feet for lines which were run using the same

satellite set for the position solution. No large depth discrepancies (greater than 5 m), were found at the MRS III related crossing points.

2. Tide Data

Testing coincided with low tide. The largest tidal variation during operations was 1 foot. This suggests that any multipath interference due to tidal fluctuation would be minimal.

VI. RECOMMENDATIONS

A. GEODETIC

1. Comparison of MVUE Position With Known WGS-72 Geodetic Station

As a truth check, the satellite receiver should be placed on a known WGS-72 geodetic station, operated in the dynamic and static mode, and the resulting positions compared to the known value. Any receiver-related systematic error would be apparent and easily removed.

2. Occupy Each Geodetic Control Station With the MVUE Receiver

In order to establish the relative position of the geodetic reference stations in the WGS-72 coordinate system, the MVUE satellite receiver should be set over each position and operated in both the static and dynamic modes for each satellite set. This would provide station coordinates compatible with the satellite system and free from errors involved in coordinate transformations. The positions would also reflect any biasing in the MVUE solution.

3. Survey Geodetic Control Stations on WGS-72 Datum

For a tighter control on positioning comparisons, all the reference stations could be surveyed in WGS-72 coordinate system by acceptable methods, then occupied by the MVUE in the dynamic and static modes. No statistical

manipulation and application of a single offset vector would be required, since the stations would be independent of one another and have unique offsets.

B. MRS III

1. Redundant Range Observation

Although the two remote reference stations provided adequate positioning information, loss of signal due to range holes or antenna interference (ship's mast) occurred at various times. This problem could have been reduced by using a third reference station. The redundant observation would also serve as a check in a least squares position solution.

2. Additional Calibration Sites

Additional calibration sites should be added at greater ranges (on the order of 7,000 to 10,000 m) to further define the range error-distance relationship. The greater degree of certainty provided by the extra range values would permit more reliable determination of range corrections for the reference stations.

3. Time of Calibration

Another aspect of calibration which may influence the range correction values involves the time of day at which the calibration takes place. Though this project involved only night operations, calibration measurements were conducted during daylight hours. As a result, the

degree to which the corrections are biased is unknown. To remove this factor as a potential error source, calibration should be made during a period when normal operations are scheduled.

4. Calibration Adjustment

To avoid the need to post-process uncorrected range data, the range corrections for a reference station should be established prior to an operation and removed by either adjustment of the instrumentation or by real-time signal processing. Any range drift could be checked by less rigorous calibration methods on a daily basis.

5. Time Delay

The one second time delay encountered with the MRS III system could be removed by operating the system in the automated event mode. This status permitted data to be gathered and presented automatically at predetermined intervals (2 second minimum).

C. GPS

1. Satellite Related Information

After completion of the test it was found that requests could be made to Vandenberg AFB to update the satellite ephemeris at earlier times than normally scheduled. Had this been known, increased post update operating time would have provided more useable data for the statistical comparison. Other information which is

available to system users are User Range Error (URE) plots on the GPS performance, satellite elevation angles and azimuth angles, satellite rise and set times, range and range-rate data for each satellite, and geometric dilution of precision information.

2. Training

Training on the operation of the manpack receiver took place during actual testing. This turned out to be a handicap because useful features of the receiver became apparent only after some time. It is recommended that at least a couple of days be invested in pre-test familiarization with the equipment. Aspects of the MVUE which deserve attention before scheduled testing are the capability of the receiver to prevent specific satellites from entering the position solution, establishing which satellites are contributing to the position solution, removing bad satellites from a solution set, and determining what is required to reacquire satellites when lost due to power failures or weak signals.

3. MVUE Data Logger

A major limitation to recording the satellite data was the lack of automatic data logger to interface with the MVUE receiver. As a result, data acquisition was confined to the maximum display rate (15 seconds) of the CDU of the manpack and subject to the errors involved with manual

recording. Automatic recording equipment for the MVUE exists and, if made available, should be used to record time and satellite data.

4. Antenna Cable Length

The length of the manpack antenna cable became a problem during the first night of ship operation. It was discovered that the preamplifier on the antenna was not designed to drive a strong signal through the 25 meters of cable needed to reach the test center. As a result, the test center had to be split into two areas, with the MVUE located at a point closer (5 meters) to the antenna location. The pretest familiarization could also double to test for such limitations of the system, thereby eliminating problems during the scheduled testing.

VII. CONCLUSIONS

With updated satellite ephemeris and using stable sets of satellites, results indicate that the MVUE manpack will provide the accuracy required for standard large scale coastal hydrographic operations of 1:80,000 and smaller by the 0.5 mm criteria (40 m). These scales are based on offset values corrected only for the error sources, totalling 7 m, found in Table II.

What is not readily apparent in this statement is that associated with each satellite set is a preferred offset bias (direction and azimuth) compared to the MRS III positions. This offset is relatively consistent in magnitude and direction from day to day. The indication is that the velocity, 25 m/s, assumed in the dynamic mode of MVUE operation is the biasing factor. If the direction of this bias is known for each satellite set on a daily basis and removed, the accuracy of the positions may be suitable for survey scales of 1:40,000 by 0.5 mm standards (20 m).

The major element which is currently placing the operational value of the MVUE in the 1:80,000 scale and smaller is the offset bias due to the 25 m/s velocity factor assumed in the dynamic operation of the MVUE. Once eliminated, the only remaining factor is the $\pm$ 12 m standard deviation

which agrees with accuracies, $\pm$ 10 m, cited in most literature regarding the GPS system. Further investigation of the 25 m/s velocity factor would greatly enhance the worth of the MVUE set tested in applications to large scale coastal surveys. Otherwise, a differential application of the MVUE set should adequately remove the bias.

Given the limited satellite configuration (four stable, operational satellites) and the low order operational status of the MVUE receiver (single channel, dual frequency, sequential), test results indicate that GPS will be an integral part of coastal surveys in the near future. Improvements to the dynamic position solution from the MVUE set tested will be required for real-time large scale survey applications. In the interim, the use of the more accurate GPS receivers, none of which have been tested for hydrographic applications, is another area for investigation.

APPENDIX A

[Jorgenson, 1980]

NAVIGATION EQUATIONS

Figure 8-1 illustrates an earth-centered inertial coordinate system. At zero time, the x axis passes through the intersection of the equator and prime meridian, the z axis passes through the North Pole, and the y axis completes the right-handed coordinate system. Because of earth rotation, the x and y coordinates change in longitude about 15 deg per hour. Shown in the figure are the user position (x, y, and z) and the position of Satellite No. 1 (x_1, y_1, and z_1). The range distance between the user and Satellite No. 1 is shown as R_1.

The basic equations using four satellites are

$$\sqrt{(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2} + T = R_1$$

$$\sqrt{(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2} + T = R_2$$

$$\sqrt{(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2} + T = R_3$$

$$\sqrt{(x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2} + T = R_4$$

where x, y, z, and T are user position and clock bias (unknowns); x_i, y_i, and z_i are the ith satellite position; $i = 1, 4$ (known); and R_i is the pseudo-range measurements to the ith satellite. Here the quantities R_1, R_2, R_3, and R_4 are "pseudo" ranges in that they are the sum of the actual range displacements plus the offset due to usar time error. For convenience, units have been selected such that the velocity of light is unity. Roughly speaking, if displacement is measured in feet, then time is measured in nanoseconds since the velocity of light is approximately 10^9 ft/sec. In the equations shown here, the four pseudo ranges are the measured quantities. The satellite positions are known, and the four unknowns are user position and the user clock error. It should be emphasized that while precision atomic frequency standards are used in the satellites and the monitor stations, there is no requirement for Navstar/GPS users to have a precision clock. Ordinary quartz crystal frequency standards are adequate for the user since he is continuously computing time for the four pseudo-range measurements.

The above equations are nonlinear. While it is possible to solve these equations directly as they are shown, user equipments without exception employ a much simpler linearized version of these equations. The basic navigation equations can be linearized by employing incremental relationships as follows.

Let

x_n, y_n, z_n, T_n be nominal (a priori best estimate) values of x, y, z, T

Δx, Δy, Δz, ΔT be the corrections to these nominal values

R_{ni} be the nominal pseudo-range measuremants from the ith setellite

ΔR_i be the difference between the actual and nominal measurements

Therefore:

$$x = x_n + \Delta x$$

$$y = y_n + \Delta y$$

$$z = z_n + \Delta z$$

$$T = T_n + \Delta T$$

$$R_i = R_{ni} + \Delta R_i$$

$$R_{ni} = \sqrt{(x_n - x_i)^2 + (y_n - y_i)^2 + (z_n - z_i)^2} + T_n$$

Substituting the incremental expressions into the basic equations yields

$$\sqrt{(x_n + \Delta x - x_i)^2 + (y_n + \Delta y - y_i)^2 + (z_n + \Delta z - z_i)^2}$$

$$= R_{ni} + \Delta R_i - T_n - \Delta T, \quad i = 1, 4$$

By ignoring second-order error terms, these equations can be written as

$$\sqrt{(x_n - x_i)^2 + (y_n - y_i)^2 + (z_n - z_i)^2}$$

$$+ \frac{(x_n - x_i)\Delta x + (y_n - y_i)\Delta y + (z_n - z_i)\Delta z}{\sqrt{(x_n - x_i)^2 + (y_n - y_i)^2 + (z_n - z_i)^2}}$$

$$= R_{ni} + \Delta R_i - T_n - \Delta T$$

Substituting

$$\frac{(x_n - x_i)}{R_{ni} - T_n} \Delta x + \frac{(y_n - y_i)}{R_{ni} - T_n} \Delta y + \frac{(z_n - z_i)}{R_{ni} - T_n} \Delta z + \Delta T = \Delta R_i$$

The above four equations ($i = 1, 2, 3, 4$) are the linearized equations that relate pseudo-range measurements to the desired user navigation information as well as the user's clock bias. The known quantities of the right-hand side of the equation are actually incremental pseudo-range measurements. They are the differences between the actual measured pseudo ranges and the measurements that had been predicted by the user's computer based on the knowledge of satellite position and the user's must current estimate of his position and clock bias. The quantities to be computed, Δx, Δy, Δz, and ΔT, are corrections that the user will make to his current estimate of position and clock biasas. The coefficients of these quantities on the left-hand side are the direction cosines of the line of sight (LOS) from the user to the satellita as projected along the x, y, and z coordinates. For all four equations, the coefficient in front of ΔT is unity. These linearized equations can be conveniently expressed in matrix notation and appear as

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & 1 \\ a_{21} & a_{22} & a_{23} & 1 \\ a_{31} & a_{32} & a_{33} & 1 \\ a_{41} & a_{42} & a_{43} & 1 \end{bmatrix} = \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta T \end{bmatrix} = \begin{bmatrix} \Delta R_1 \\ \Delta R_2 \\ \Delta R_3 \\ \Delta R_4 \end{bmatrix}$$

where a_{ij} is the direction cosine of the angle between the range to the ith satellite and the jth coordinate.

An examination of the solution matrix shows how divergence may occur. If the ends of the unit vectors to the four satellites are in a common plane, along a direction perpendicular to this plane the direction cosines of the four unit vectors are all equal. Suppose the coordinate frame had been selected so that the z coordinete is along this direction The determinant of the solution matrix takes the form:

$$D = \begin{vmatrix} a_{11} & a_{12} & a_3 & 1 \\ a_{21} & a_{22} & a_3 & 1 \\ a_{31} & a_{32} & a_3 & 1 \\ a_{41} & a_{42} & a_3 & 1 \end{vmatrix}$$

There are six 2 × 2 minors of this 4 × 4 determinant of the form:

$$M = \begin{vmatrix} a_3 & 1 \\ a_3 & 1 \end{vmatrix} = 0$$

Clearly then, the 4 × 4 determinant is also zero, and there is no solution possible from the four equations. In short, the navigation equations "blow up."

The situation where the ends of the unit vectors are in a common plane is very close to where the four satellites are in a common plane in space. This is what happens so often with the uniform 18-satellite constellation as discussed in Section 2.

By the use of matrix notation, the above equations can be expressed very compactly as follows.

Let

r = the four-element pseudo-range measurement difference vector

x = the user position and time correction vector

A = the 4 × 4 solution matrix

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & 1 \\ a_{21} & a_{22} & a_{23} & 1 \\ a_{31} & a_{32} & a_{33} & 1 \\ a_{41} & a_{42} & a_{43} & 1 \end{bmatrix}$$

$$x = [\Delta x \quad \Delta y \quad \Delta z \quad \Delta T]^T$$

$$r = [\Delta R_1 \quad \Delta R_2 \quad \Delta R_3 \quad \Delta R_4]^T$$

Therefore:

$$Ax = r \quad \text{or} \quad x = A^{-1}r$$

The last equation presented compactly expresses the relationship between pseudo-range measurements and user position and clock bias. Since this relationship is linear, it can be used to express the relationship between the errors in pseudo-range measurement and the user quantities. This relationship is therefore

$$\epsilon_x = A^{-1}\epsilon_r$$

where ϵ_r represents the pseudo-range measurement errors and ϵ_x the corresponding errors in user position and clock bias.

Let us now consider the covariance matrix of the expected errors in pseudo-range measurements and the covariance matrix of the user quantities. The first covariance measurement is a 4 × 4 array composed of the expected values of the squares and products of the errors in the pseudo-range measurements. The diagonal terms in the matrix, namely the squares of the expected errors, are the variances; i.e., the squares of the expected 1σ values of the pseudo-range measurement errors. The off-diagonal terms are the covariance between the pseudo-range measurements and reflect the correlations to be expected in these measurements. Likewise, the covariance matrix for the user quantities is composed of the expected values of the squares and products of the errors in the user quantities. The diagonal terms are the variance or the squares of the 1σ errors in user position and time, while the off-diagonal terms reflect the correlations in these errors. These covariance matrices are given by

$$COV(r) = E\{\epsilon_r \epsilon_r^T\}$$

$$COV(x) = E\{\epsilon_x \epsilon_x^T\}$$

where the symbol $E\{\ \}$ designates "expected value" of the quantity inside the braces.

Upon substitution, the matrix relationship between the two covariance matrices becomes

$$COV(x) = A^{-1}COV(r)A^{-T}$$

An alternate formulation for this relationship, based on a straightforward matrix algebra manipulation, is

$$COV(x) = [A^T COV(r)^{-1} A]^{-1}$$

Note that the relationship between the pseudo-range measurement errors and the user's position and clock bias errors is a function only of the solution matrix A, which in turn is a function only of the direction cosines of the LOSs from the user to the satellites along whichever coordinate system is used. In other words, the error relationships are functions only of satellite geometry. An important consideration in the proper use of Navstar/GPS is the fact that the four satellites being used must possess "good" geometric properties. (A "good" situation is one in which, because of satellite geometry, a given level of error in the pseudo-range measurements results in small user errors.) This leads to the concept of geometric dilution of precision (GDOP), a measure of how satellite geometry degrades accuracy.

The following assumption regarding pseudo-range measurement errors provides a method of quantitatively determining whether a particular four-satellite geometry is good or bad. Let each individual pseudo-range measurement have an error (1σ) of unity, where the expected mean is zero and the correlation of errors between satellites is also zero. With these assumptions, the covariance matrix for the errors in the pseudo-range measurements becomes a 4 × 4 unity matrix. Thus, for this case, the covariance matrix for user position and clock bias errors is given by

$$COV(x) = (A^T A)^{-1}$$

GDOP is defined as the square root of the trace of COV(x) when COV(r) is an identity matrix.

Therefore:

$$GDOP = \sqrt{TRACE\left[(A^T A)^{-1}\right]}$$

Some properties of this quantity can be summarized as follows:

a. GDOP is, in effect, the amplification factor of pseudo-range measurement errors into user errors due to the effect of satellite geometry.

b. GDOP is independent of the coordinate system employed.

c. GDOP is a criterion for designing satellite constellations.

d. GDOP is a means for user selection of the four best satellites from those that are visible.

By letting V_x, V_y, V_z, V_T be the variances of user position and time, we have

$$GDOP = \sqrt{V_x + V_y + V_z + V_T}$$

As an alternative to GDOP as a criterion for selecting satellites or evaluating satellite constellations, only some of the variances of user position and time might be used. These are defined as follows:

PDOP — The square root of the sum of the squares of the three components of position error

HDOP — The square root of the sum of the squares of the horizontal components of position error

VDOP — The altitude error

Note: $PDOP^2 = HDOP^2 + VDOP^2$

TDOP — The error in the user clock bias multiplied by the velocity of light

Note. $GDOP^2 = PDOP^2 + TDOP^2$

The alternative criterion most frequently used is the position dilution of precision (PDOP). PDOP is also invariant with the coordinate system and is used because the most important consideration in any navigation system is position accuracy, knowing time is generally a secondary by-product. Another alternative is the horizontal dilution of precision (HDOP), which is most meaningful for users who are using the system primarily to obtain horizontal position.

APPENDIX B

Horizontal Control

NAME	QUAD	STATION	LATITUDE	LONGITUDE	ELEVATION (METERS)	SOURCE	ORDER
LUCES POINT	36214	1051	36°38'10".524N	121°55'38".399W	6.000	CGS	3^{rd}
MUSSEL 1932	36214	1062	36°37'18".151N	121°54'11".628W	6.085	CGS	3^{rd}
MONTEREY BAY 4	36214	1055	36°37'31".128N	121°50'31".728W	49.800	CGS	3^{rd}
SEASIDE 4	36214	1080	36°36'23.446N	121°51'38".833W	-	CGS	3^{rd}
USE MONUMENT	-	-	36°36'04".686N	121°52'35".904W	14.749	CE	2^{nd}
NAIL	-	-	36°36'31".953N	121°53'25".156W	2.507	NPS	3^{rd}

CE - CORPS OF ENGINEERS

CGS - COAST AND GEODETIC SURVEY

NPS - NAVAL POSTGRADUATE SCHOOL

SATELLITE OBSERVATION TEAM

STATION OCCUPATION REPORT

This report will provide information for recovery and occupation of each Satellite Doppler Station. It shall be completed and submitted as soon as all observations are finished.

1. Station Report Date 18 April 1976

System Reporting (circle one) JMR-1 GEOCEIVER (SN 063)

STATION NAME CIRRIS PT 2-A 75 STA NO 10213

LOCATION Monterey, California

2. Geodetic Position Datum NAD 1927

Lat. N 36° 37' 55".137 Long. W 121° 56' 01".221 Elev. 22.833 m MSL

Source HAVOC Adjustment (26 Feb 1975) DMAAC GSS

3. Name and address of site owner.

U. S. Navy
1352 Lighthouse Avenue
Pacific Grove, CA 93950
ATTN: Officer-in-Charge

WGS-72
36 37 54.836 121 56 05.625
-15.64 (W)

Name and mailing address of Party Chief at station.

Site:
TSgt Ted S. Martin
c/o General Delivery
Pacific Grove, CA 93950

Organization:
TSgt Ted S. Martin
DMAAC GSS
ATTN: ODTS
F. E. Warren AFB WY 82001

4. Site Occupation

	GCD #	Date		GCD #	Date
Arrival Date	050	19 Feb 76	Departure Date	057	26 Feb 76
Date 1st Obsn	051	20 Feb 76	Date last Obsn	057	26 Feb 76
Orbit or Event No	26948		Orbit or Event No	11585	
Satellite Ident No	68		Satellite Ident No	77	

DOPPLER RECEIVER GEODETIC SUMMARY SHEET

STATION DESIGNATION CIRRIS PT 2-A 75	STATION NO	POSITIONAL DATA REFERRED TO	MODEL JMR-1
LOCATION Monterey, CA	10211	Center of Station Mark	SN 063

ELEVATION OF MARK ABOVE MSL (GEOID)	HEIGHT OF TRACKING EQUIPMENT REF. PT. ABOVE STATION MARK
22.833 METERS ±	1.941 METERS

GEODETIC COORDINATES (SURVEY)

DATUM	φ	λ	h*
NAD 1927	N 36° 37' 55".137	W 121° 56' 01".221	-7.826 m
WGS 72	N 36° 37' 54".836	W 121° 56' 05".625	-15.640m

ASTRONOMICAL COORDINATES

SOURCE	φ	λ

DOPPLER DATA

DATUM	φ	λ	h*
(WGS-66 coord.) NWL-9D	N 36° 37' 54".859	W 121° 56' 05".885	-20.110 m

DATUM	x	y	z
NWL-9D	-2710616.898 m	-4348869.771 m	3784683.186 m

REMARKS: * h= HEIGHT ABOVE THE ELLIPSOID

Data is from satellites 68 and 77 from 20-26 Feb 1976.
47 passes were collected, 46 were used in the final solution.
The NWL precise emphemeris was held fixed in the solution.
The standard errors of the final solution are:

σ_ϕ = 0.025 seconds

σ_λ = 0.068 seconds

σ_H = 0.975 meters

(If more space is required use reverse side)

EXECUTED BY: CMSgt Raymond	DATE	CHECKED BY:	DATE
AGENCY: DMAAC CSS	Apr 76	Mr. Nollie R. Goff	May 76

ATC FORM 8290-1 NOV 73 REPLACES TPS FORM 110-84, SEP 70, WHICH IS OBSOLETE

SATELLITE OBSERVATION TEAM

S T A T I O N   O C C U P A T I O N   R E P O R T

This report will provide information for recovery and occupation of each Satellite Doppler Station. It shall be completed and submitted as soon as all observations are finished.

1. Station Report Date 14 Nov 76

System Reporting (circle one) JMR-1 GEOCEIVER (SN 063)

STATION NAME LORAN C STA NO 10277

LOCATION Pt. Pinos, California

2. Geodetic Position Datum WGS-72 h

Lat. N36° 38' 12".226 Long. W121° 56' 38".58 ~~ELEV~~ h (ellipsoid) -29.065m

Source JMR-1 Observations

3. Name and address of site owner.

United States Coast Guard
San Fransico, California

Name and mailing address of Party Chief at station.

Site:	Organization:
Capt George A. Lafferty	GSS/DMATC
General Delivery	DA3
Pacific Grove, CA	F. E. Warren AFB, WY 82001

4. Site Occupation

	CCD #	Date		CCD #	Date
Arrival Date	310	5 Nov 76	Departure Date	319	14 Nov 76
Date 1st Obsn	313	8 [illegible] 76	Date last Obsn	318	13 Nov 76
Orbit or Event No	30531		Orbit or Event No	47301	
Satellite Ident No	68		Satellite Ident No	58	

SUMMARY OF SATELLITE-OBSERVED STATION

STATION NAME / LOCAL NUMBER	LOCATION	DOPPLER NO.
Pt. Pinos [illegible] LORAN C	Pt. Pinos, CA	10277
[illegible]: JBR STA 10277		
AGENCY (CAST IN MARK): Defense Mapping Agency	TYPE OF STATION MARK: Standard Brass Disk	

DOPPLER OBSERVATIONS

EQUIPMENT/SERIAL NO.	HEIGHT OF TRACKING EQUIPMENT REFERENCE POINT ABOVE STATION MARK:	TRACKING EQUIPMENT REFERENCE POINT
063	1.085	Electrical Center
OBSERVED BY (AGENCY): DMATC(GGS)	SATELLITE(S) OBSERVED: 58 and 68	PERIOD OF OCCUPATION: 5-14 Nov 76

SATELLITE-DERIVED COORDINATES

PASSES ACCEPTED	DEGREES OF FREEDOM	RESIDUAL RMS	STATION SET	GRAVITY MODEL	ELLIPSOID	MINIMUM E[illegible] ANGLE
27	N/A	1m	NWL 9D	10E	8E	[illegible]

(Satellite-derived coordinates referred to station mark)

φ	λ	h	ACCURACY
N36° 38' 12".49	W121° 56' 08".818	-33.535	1.0m in each Axis 1σ.
X	Y	Z	
-2710503.847m	-4348550.637m	3785105.726m	

(Satellite-derived coordinates of station mark transformed to local datum)

φ	λ	h	DATUM
X	Y	Z	ELLIPSOID
ΔX	ΔY	ΔZ	DATE OF TRANSFORMATION

GROUND SURVEY COORDINATES OF STATION MARK

φ	λ	DATUM (HORIZONTAL)	ELLIPSOID
N36° 38' 12".509	W121° 56' 04".131	NAD-27	Clark 1866

DATE OF ADJUSTMENT	ORDER	SURVEY BY (AGENCY)	DATE	LOCATION OF SURVEY DATA
Dec 76	3rd	DMATC(GGS)	Dec 76	F.E. Warren AFB, WY [illegible]

ELEVATION (H)	DATUM (VERTICAL)	GEOID HEIGHT (N)	ELLIPSOID HEIGHT (h)
N/A	N/A	N/A	N/A

ORDER (ELEV.)	ESTABLISHED BY (AGENCY)	DATE	SOURCE OF (N)
N/A	N/A		N/A

CONNECTION TO LOCAL CONTROL

FROM	TO	( ) AZ FROM NORTH	DISTANCE

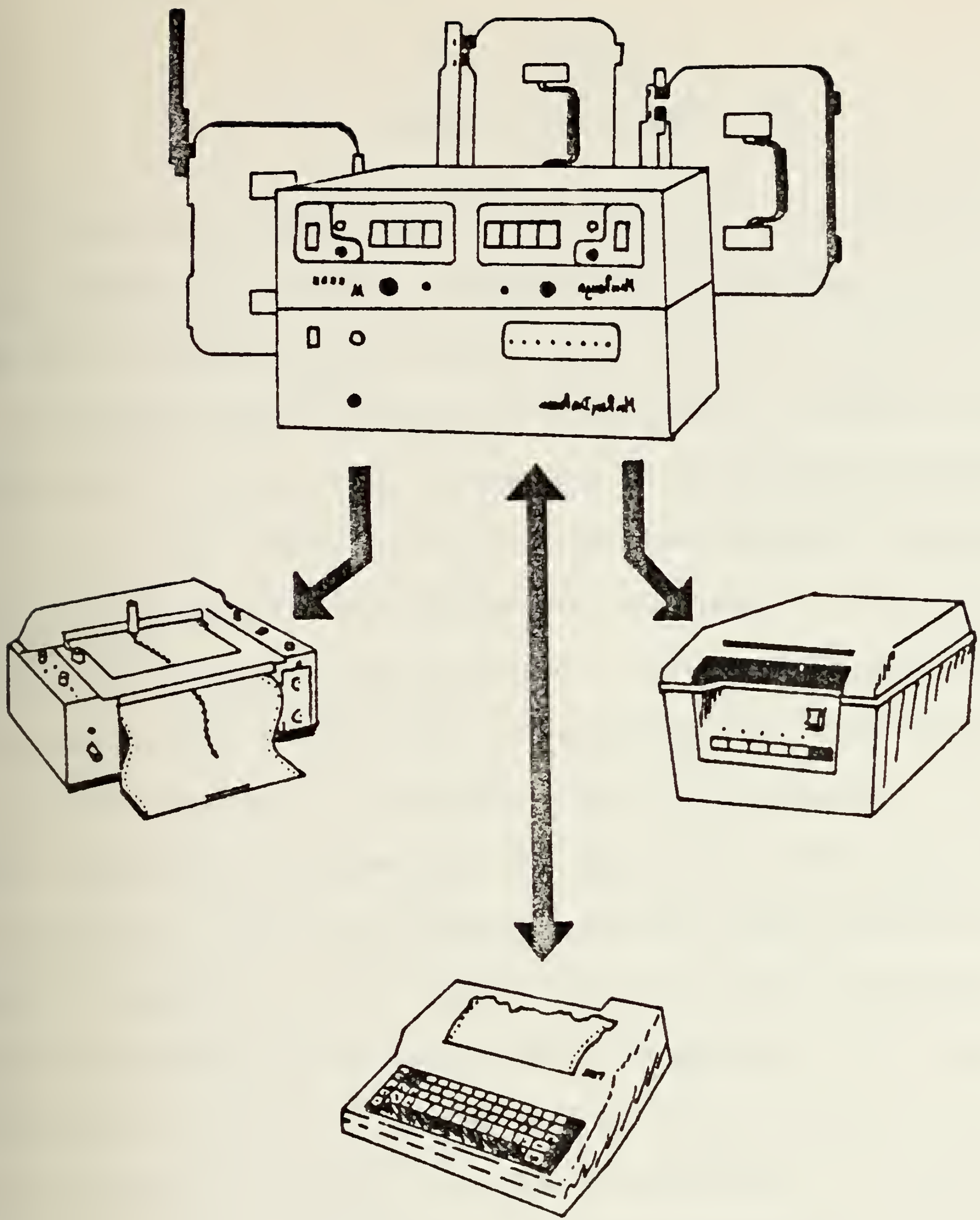
REMARKS

OTHER RELATED DATA FOR THIS STATION

DATA	AVAIL.	LOCATION/REMARKS
STATION OCCUPATION REPORT	X	
GEODETIC INFORMATION REPORT		
STATION DESCRIPTION	X	
SURVEY DIAGRAM	X	
STATION [illegible] SKETCH		
PHOTOIDENTIFICATION		
ASTRONOMIC COORDINATES		
STATION [illegible]		

PREPARED BY/DATE	CHECKED BY/DATE	REVISED BY/DATE	CHECKED BY/DATE
Goff/Mar 77	Mitchell/Jun 77		

DMA FORM 8270-1-R



APPENDIX C

Mini Ranger III System Description

MRS III

(MOTOROLA MINI-RANGER III)

The MRS III, manaufactured by Motorola, Inc., is a short range position-fixing system designed for vessels, aircraft, and land vehicles. The MRS III, operating on the basic principle of pulse radar, uses a transmitter aboard the surface vessel to interrogate radar transponder reference stations located over geographically known points. When a signal transmitted by the receiver-transmitter is received, the range counter begins to count. After five sequential interrogations and receptions of five replies from a transponder, the count is displayed on the range console front panel as range to the transponder. This range together with channel and code information are also transmitted in parallel binary coded decimal (BCD) format from a rear-panel connector to peripheral printers and computers. Channel A and channel B range data are gathered and displayed within 10ms during each sample period of operation. Elapsed time between transmitted interrogations produced by the MRS III transmitter and the reply received from each transponder is used as the basis for determining the range to each transponder. This range information, displayed by the MRS III together with the known location of each transponder, can be trilaterated to provede a position of the vessel. .The standard MRS III operates in the C-band frequencies at line-of-sight ranges up to 37 km. The probable range measurement accuracy is stated as 2 meters.

[Extracted from NOAA Hydrographic Manual, Appendix A, 1976]

BASIC SYSTEM SPECIFICATIONS

Range	37 km (20 nm) line of sight; 20 to 200 km (10 to 108 nm) options available
Accuracy	±2 meters (6.5 ft.) probable range error.
Frequency	5400 to 5650 MHz.
Coding	Four selectable codes using pulse spacing (16 code optional encoder)
Range Console	
Range readout	Displays channels A and B simultaneously with range units available in meters (standard); yards or feet optional.
Output to peripherals	Binary coded decimal, TTL. +8421 parallel. RS-232C serial output optional.
Operating voltages	115/230 volts AC, 50-400 Hz (+12 to +32 volts DC power).
Power consumption	77 watts (AC); 57 watts (DC)
Operating temperatures	0 to +50°C.
Dimensions	43 x 45.7 x 14 cm (17 x 18 x 5.5 in.) table mount.
Weights	14.5 kg (32 lb)
Control Station Receiver/Transmitter Unit	
Antenna	6 dB omnidirectional (25° elevation)
Operating temperatures	-50° to +60°C.
Power	Supplied by range console.
Dimensions	15 x 20 x 30 cm (6 x 8 x 12 in.).
Weight	-4.3 kg (9.5 lb) with brackets.
Remote Reference Stations	
Antenna	13 dB sector (75° azimuth, 15° elevation).
Operating voltages	22 - 32 volts DC
Power consumption	13 watts (nominal), 8.5 watts (standby).
Operating temperatures	-50° to +60°C.
Dimensions (nominal)	15 x 20 x 30 cm (6 x 8 x 12 in.)
Weight	4.3 kg (9.5 lb), less antenna.

[MOTOROLA, 1979]

APPENDIX D
Tellurometer

Tellurometer Model MRA5 is a portable, versatile, electronic distance measuring system, capable of measuring distances from 100 meters to at least 50 kilometers.

The Tellurometer system of distance measurement effectively equates the total number of radio wavelengths and fractions of a wavelength between two stations to the distance separating them. The stations are termed the "Master" and the "Remote", the double distance (Master to Remote + Remote to Master) being measured and the final reading obtained from the Master instrument.

The MRA5 instruments (Serial number 1502 and 1504) used to measure the calibration baselines were on loan to the Hydrographic Program of the Naval Postgraduate School by the National Oceanic and Atmospheric Admininistration (NOAA).

Table -1 is the calibration information for the two instruments.

TELLUROMETER MRAS OBSERVATIONS

STATE: Virginia LOCALITY: Corbin DATE: May 3, 1977

CORBIN BASE LINE (Geodetic distance = 1000.009m)

Instrument Serial Numbers From	To	Slope Distance(m)	Mean	Geodetic Distance(m)	Corbin Base Line(m)	Instr. Zero Constant(m)
1501	1503	1000.136 1000.128	1000.132	1000.118	1000.009	-0.109
1503	1501	1000.046 1000.046	1000.046	1000.032	1000.009	-0.023
*1502	1504	1000.017 1000.014	1000.016	1000.002	1000.009	+0.007
*1504	1502	1000.016 1000.022	1000.019	1000.005	1000.009	+0.004

BALLARD - CORBIN BASE LINE (Slope distance = 14,433.307m)

Instrument Test Measurements

Instrument Serial Numbers From	To	Measured Slope Distance(m)	Established Slope Distance	Difference	Error
1501	1503	14,433.309	14,433.307	+0.002	1/7,216,500
1501	1503	14,433.347	14,433.307	+0.040	1/360,825
1503	1501	14,433.119	14,433.307	-0.188	1/76,771
1503	1501	14,433.227	14,433.307	-0.080	1/180,412
*1502	1504	14,433.213	14,433.307	-0.094	1/153,542
1502	1504	14,433.180	14,433.307	-0.127	1/113,646
*1504	1502	14,433.182	14,433.307	-0.125	1/115,464
1504	1502	14,433.113	14,433.307	-0.194	1/74,397

All instruments operated properly.

NOTICE: The above data is from field computations.

*MRAS instruments used for baseline measurements.

Figure D-1

APPENDIX E

TEST PLAN
FOR
GPS/HYDROGRAPHIC APPLICATIONS TEST

APRIL-MAY 1980

P. DUNN and J. REES

NAVAL POSTGRADUATE SCHOOL

TABLE OF CONTENTS

SECTION I

INTRODUCTION

1.1 Purpose. This plan presents the scope and requirements for the operations necessary to conduct the Hydrographic Positioning field test of the NAVSTAR Global Positioning System (GPS) equipment to be installed on the R/V ACANIA.

1.2 Scope. Equipment to be tested includes the Manpack/Vehicular User Equipment (MVUE) to be installed on the R/V ACANIA. This equipment is a Phase I Advanced Development Model. Section 6 provides a more detailed description of the equipment. The basic objective of the tests are to evaluate the performance and accuracy of the ship installed set, including the effects of multipath and Radio Frequency Interference (RFI) and ship dynamics, and to perform an operational hydrographic demonstration of the MVUE Equipment. The test data collected and evaluated will be used to satisfy partial requirements for a Master's in Oceanography/Hydrography and also to determine whether the MVUE is suitable as a hydrographic tool.

This plan is one of a series of documents related to the program of testing being conducted. The plan extracts, summarizes and coordinates planning information provided by the contractor (Texas Instruments, Inc.) and higher authority (Thesis Advisor, NPS) and defines general operating requirements and scenarios for conduct of the tests. These requirements will in turn be used to prepare detailed operating procedures to execute the tests.

Tests to be conducted under this plan are:

(1) Visual Inspection (VI)
(2) Power Stability (PS)
(3) Operation Check (OC)
(4) Truth Check (TC)
(5) Static Technical Performance (ST)
(6) Beach Test (LT)
(7) Pier Test (PT)
(8) Anchor Test (AT)
(9) High Dynamics Test (DT)
(10) Survey Scenario (SS)

The tests will be performed during the period 28 April through 6 May 1980.

SECTION II

APPLICABLE DOCUMENTS

2.1 Documents List. The following documents provide information related to this plan:

a. Global Positioning System Control/User Segments, System Design Trade Study Report, General Dynamics/Electronics Division, F04701-73-C-0298, Feb. 1974.

b. Global Positioning System Control/User Segments, Final Report, Vol. I through Vol. IV, General Dynamics/Electronics Division, F04701-73-C-0298, Feb. 1974.

c. Global Positioning Systems (GPS) Manpack/Vehicular User Equipment (MVUE); Final Report, Vol. I; Reference Volumes II and III, Texas Instruments, Inc., F04701-75-C-0181, 15 Aug. 1979.

d. Global Positioning Systems (GPS) Manpack/Vehicular User Equipment (MVUE); In-Plant Test Report, Texas Instruments, Inc.; F04701-75-C-0181 (A017), 11 June 1979.

e. Prime Item Product Function Specifications for the Global Positioning System (GPS); Manpack/Vehicular Positioning and Navigation Set Type C1A; Texas Instruments, Inc.; CID-ADUE-101A; 3 June 1975.

f. NAVSTAR Global Positioning System, LTVP Field Test Operations Plan, SAI Comsystems, N00123-77-C-0046, 7 Nov. 1979.

g. NAVSTAR Global Positioning System, FRIGATE/FF-1052 Field Test Operations Plan, Naval Oceans Systems Center (NOSC), FTOP-FF-1052, July 1978.

SECTION III

TESTING REQUIREMENTS

3.1 General Requirements

3.1.1 Performance Criteria. Criteria for the test performance may be divided into functional criteria and quantitative criteria. Functional performance involves the performance of functions and operations which are specified performance capabilities, such as entry of initialization parameters or switch selection of an operating mode. Functional performance is tested on a "GO/NO GO" basis, i.e., whether or not the operation performs correctly. Quantitative performance involves those areas of system operation for which there are specified numerical criteria such as time-to-first-fix (TTFF), calculation tolerances, or fix accuracies. Table 3-1 lists selected numerical criteria. (Field performance may deviate somewhat from specified values; this will be subject of a post-test analysis.) Figure 3.1 lists the MVUE Operating Functions to be observed during the tests.

3.1.2 System Requirements. The NAVSTAR Global Positioning System is a space-based radio positioning and navigation system that provides extremely accurate three-dimensional position data, velocity information and system time to suitably equipped users anywhere on or near the earth. The Global Positioning System consists of three major segments: space system segment, control system segment, and user system segment. The manpack (MVUE) is in the user system segment.

The operational space system segment deploys three planes of satellites in circular 10,898 nautical mile orbits. Each satellite has an orbital inclination of 63^{0} and a 12-hour period. Each plane has eight satellites. This deployment provides the satellite coverage for continuous three-dimensional positioning navigation, and velocity determination. Each satellite transmits a composite signal at two L-band frequencies consisting of a precision (P) navigation signal and a coarse/acquisition (C/A) navigation signal. The navigation signals contain satellite ephimerides, atmospheric propagation correction data, and satellite clock bias information provided by a master control station. In addition, the second L-band navigation signal permits the user to correct for the ionospheric group delay or other electromagnetic disturbances in the atmosphere.

TABLE 3-1. MVUE SELECTED NUMERICAL CRITERIA

PARAMETER	VALUE	SOURCE
Equipment Stabilization Period	13.5 minutes	2.1 c, Vol. II sec. 2.1.1.a
Signal Source Elevation	10^{0} above antenna horizon	2.1 c, Vol. II sec 4.4.1
Signal Sensitivity	-130 dBm for L1 C/A -133 dBm for L2 P	2.1 d sec 3.2.2.1 sec 3.2.2.3
Time-To-First-Fix (TTFF)	4 minutes (static) 5 minutes (dynamic)[1]	2.1 d Pg. 93
Navigation	Static CEP 15m. Dynamic CEP 50m.	2.1 d Pg. 93
Range Measurement Accuracy	1.47 m.	2.1 d Pg. 93

1. Dynamic Velocity is 25 m/s with $1 m/s^2$ acceleration in turns.

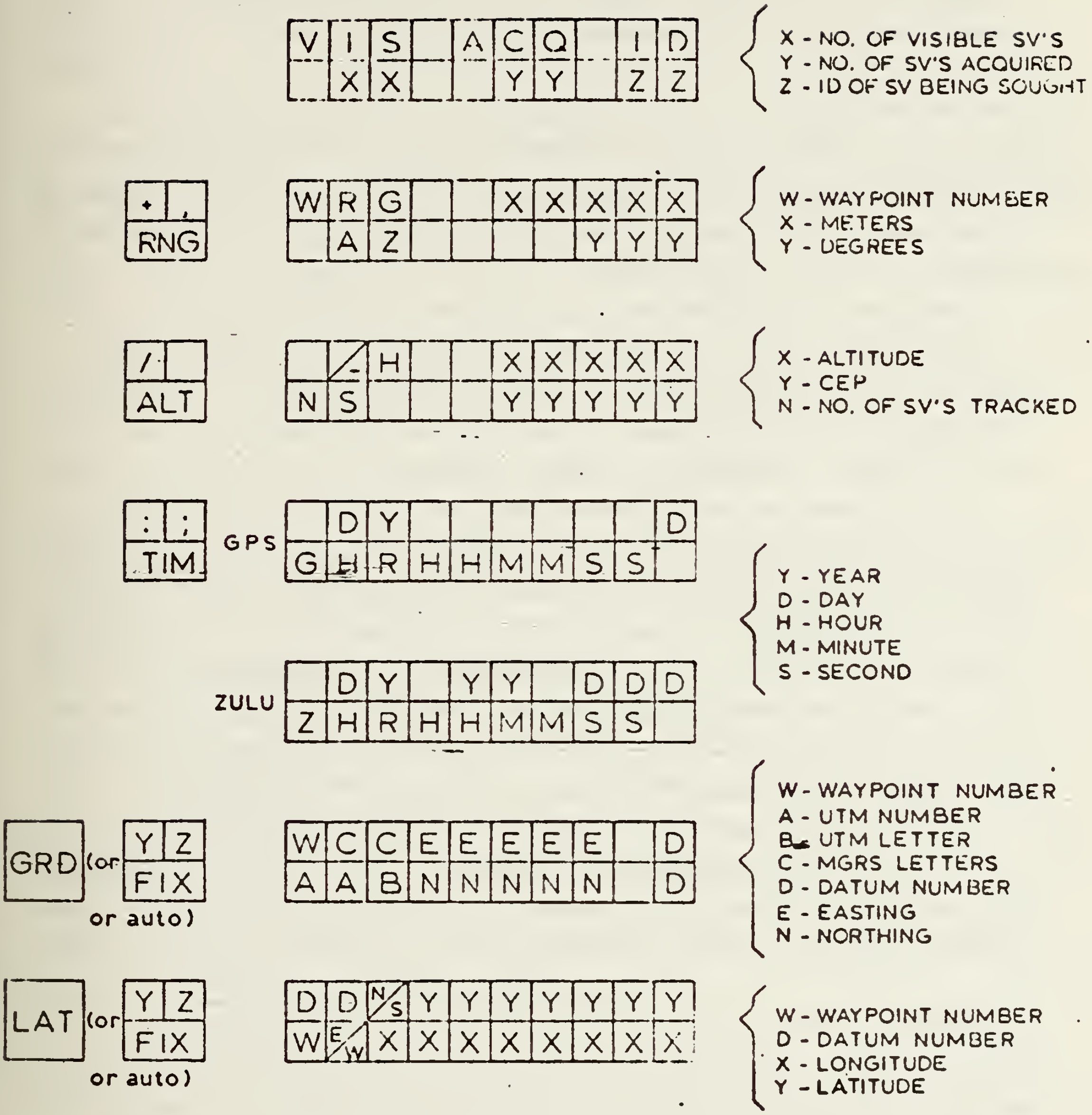


FIGURE 3-1. MVUE OPERATING FUNCTIONS

In the control system segment, four widely separated monitor stations, located in U.S. controlled territory, passively track all satellites in view and accumulate ranging data from the navigation signals. The ranging information is processed at a master control station located in the continental United States to use in satellite orbit determination and systematic error elimination.

The orbit determination process derives progressively refined information defining the gravitational field influencing spacecraft motion, solar pressure parameters, location, clock drifts, and electronic delay characteristics of the ground stations, and other observable system influences. An upload station located in the continental United States transmits the satellites' ephemerides, clock drifts, and propagation delay data to the satellites as required.

Each of the satellites and ground transmitters in this system emit a carrier which is modulated with a pseudo-random noise code of very low repetition rate. The generation of this code is synchronized to the satellite clock time reference. The manpack receiver also maintains a time reference used to generate a replica of the code transmitted by the satellite. The amount of time skew that the receiver must apply to correlate the replica with the code received from the satellite provides a measure of the signal propagation time between the satellite and the manpack. This time of propagation is called the pseudo-range measurement since it is in error by the amount of time synchronization error between the satellite and receiver clocks. The receiver also measures the Dopplier shift of the carrier signals from the satellite. By measuring the accumulated phase difference in this Doppler signal over a fixed interval, the receiver can infer the range change increment. This measurement is called the delta pseudo-range measurement and is in error by an amount proportional to the relative frequency error between the emitter and receiver clocks. Since the carrier wavelength is shourt, the delta pseudo-range is a finely quantified measurement.

The satellites also transmit precise ephemeris and satellite clock data (ground transmitters provide their earth fixed coordinates). These estimates are obtained by tracking the satellites from several ground monitor stations.

The manpack (MVUE) is thus able to obtain measures of pseudo-range and delta-range reception of these measurements, ephemeris data and emitter clock calibration data. Measurements from four satellites provide the manpack with sufficient information to solve for three components of user position, velocity and user clock error. To accomplish the navigation function, pseudo-range and

delta-range measurements are used to update a running estimate of user position.

The general system test configuration is shown in Figure 3.2. Figure 3-3 indicates the general layout of the R/V ACANIA. System operating testing requirements include the following:

(1) The Master Control System Station at Vandenburg Air Force Base will provide normal satellite control functions, including daily ephemeris updates and weekly almanac updates.

(2) The User Equipment software shall be identified and documented by the contractor as to all deviations from the specification configuration. An objective shall be to provide patch-free software with an error-free assembly. Configuration control of the software will remain a responsibility of the contractor.

(3) R/V ACANIA interface requirements for the hydrographic test conducted under this plan include physical mounting of the MVUE, associated instrumentation, test antenna, and antenna cabling.

<u>3.1.3 Test Documentation</u>. Documentation for these tests are Test Plans, Test Procedures, and Test Reports. These documents are described in the following paragraphs:

a. <u>Test Plans</u>. Test plans include general GPS plans; this operations plan provided and maintained by Dunn/Rees (The technical plans for the Field Checkout Tests and Operational demonstration to be provided by the contractor).

b. <u>Test Procedures</u>. Test procedures to be generated by Dunn/Rees will include detailed R/V ACANIA operations procedures and events and technical procedures for operation of the MVUE and Mini-Ranger III tracking system.

c. <u>Test Reports</u>. An initial report will be provided as an overview of significant events and observations and summary report of the test results to be included as part of the thesis.. Data collection and test reporting requirements are described in Section 9.

<u>3.1.4 Operations</u>. Requirements for ship's operations are based on the need to cover the full range of maneuvering functions which should impact GPS User Equipment performance. Critical maneuvering parameters include:

(1) Ship's Heading - to encompass 360 degrees of rotation.

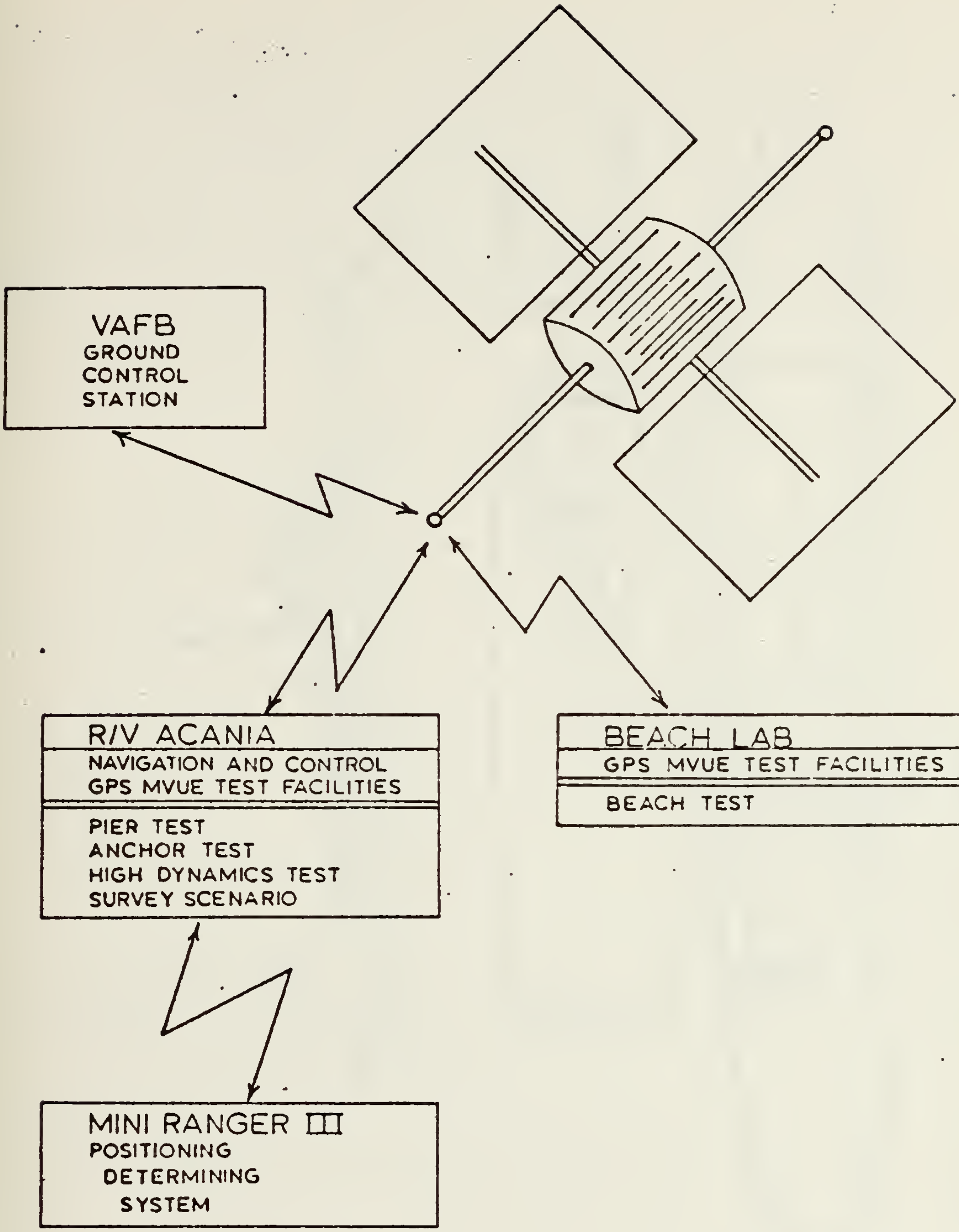


FIGURE 3-2. ACANIA/MVUE GPS SYSTEM TEST CONFIGURATION

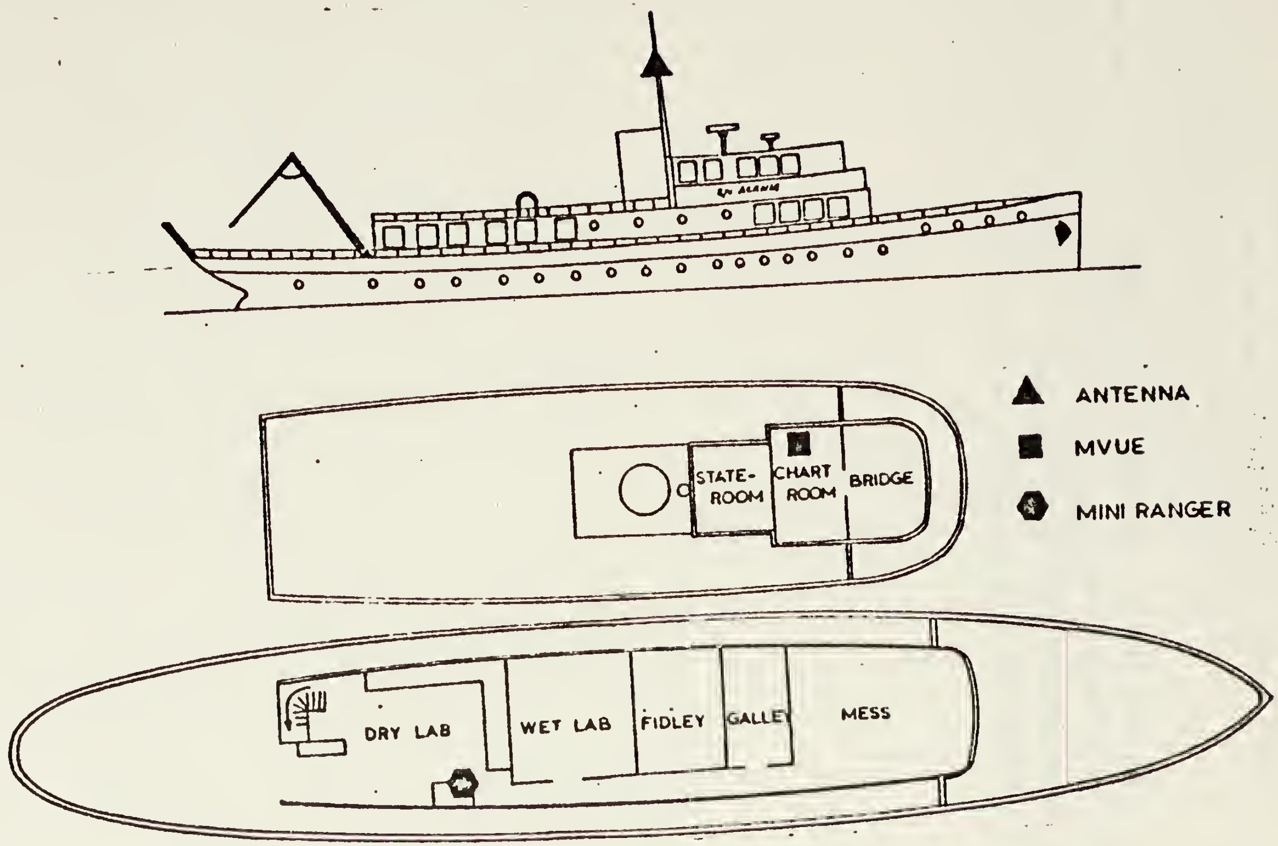


FIGURE 3-3. R/V ACANIA LAYOUT

(2) Ship's Speed - Ranging from 0 to 9 knots.

(3) Ship's Roll - to encompass the maxinum possible ship roll for at least 30 minutes, repeated in the orthogonal roll plane. (This parameter is dependent upon the available sea state.)

Figure 3-4 shows general operations plan for all tests.

Table 3-2 provides a cross-reference of the required test operations for the manpack (MVUE) and indicates what tests are to be performed during each day of the test period. Ship's support for these operations will include exercise of all ship control functions, maintainance of accurate course and heading, and voice coordination as needed.

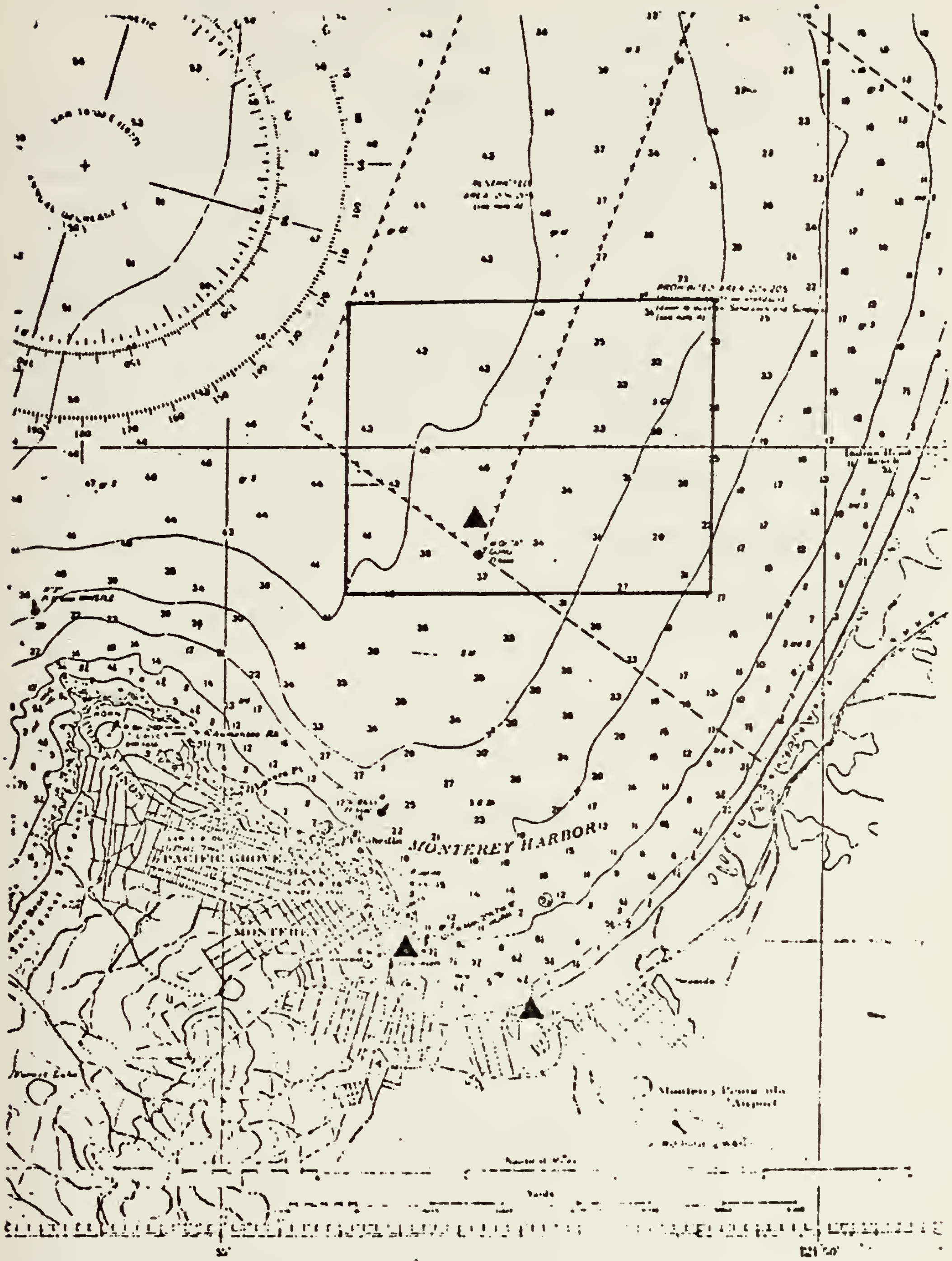


FIGURE 3-4. GENERAL OPERATING AREA

TABLE 3-2. GENERAL TEST OPERATION

TEST PERIOD: 29 APRIL TO 7 MAY 1980*

TEST TITLE	LOCATION[1]	TYPE OF TEST
Visual Inspection (VI)	A	Platform
Power Stability (PS)	A	Compatability
Operational Check (OC)	A	Tests
Truth Check (TC)	P,H,S	
Static Technical Performance Test (ST)	A	
Beach Test (LT)	B	Static Performance
Pier Test (PT)	P	Low-Dynamic Technical Performance
Anchor Test (AT)	H	Medium-Dynamic Technical Performance
High Dynamics Test (DT)	H	High-Dynamic Technical Performance
Survey Scenario (SS)	H,S	Operational Performance
a) Circle		
b) 5-knot Lattice		
c) 9-knot Lattice		

* Indicates a one day extension if needed

1. A - All locations
   B - Beach
   P - Pier
   H - Harbor
   S - Scenario

3.2 Visual Inspection. The Visual Inspection test shall perform a complete inspection of the MRS III reference stations, and the MVUE installations at desired locations.

3.2.1 Pretest Conditions. The MRS III reference stations shall be set up each night at designated locations. The MVUE will be installed either on the beach or on ship as conditions determine.

3.2.2 Test Inputs. No test inputs are required for this test.

3.2.3 Expected Accuracies. The power cables, antenna cables, interface connections, antenna mountings, and equipment mountings will conform to specifications.

3.2.4 Expected Output Values. The Mini-Ranger III and MVUE shall conform to specifications including proper mounting, cabling, and satisfactory workmanship. The MRS reference stations and master station shall communicate. The Test Director shall certify that all systems are ready for testing.

3.2.5 Data Collection Method. The test observer shall enter in the test log any discrepancies found in the MRS III or MVUE installation.

3.2.6 Timing Requirements. No timing requirements have been identified for this test.

3.2.7 Degradation. This test should have no effect on system operating capability.

3.2.8 Casualty Recovery. No casualty recovery has been identified for this test.

3.2.9 Display. Not applicable.

3.3 Power Stability. The power stability test shall measure the power characteristics of the R/V ACANIA power system. This test shall be performed if the vehicle power adapter is utilized as a power converter; otherwise optional.

3.3.1 Pretest Conditions. The visual inspection test shall be performed prior to this test.

3.3.2 Test Inputs. The R/V ACANIA shall be energized and readings of voltage, ripple, and stability over an extended operating period shall be gathered. Measurements shall be taken for load and no-load conditions.

3.3.3 Expected Accuracies. The required accuracies of the MVUE are:

(1) voltage 24 V $\pm$ 4

(2) ripple max 500 Hz, 1 V_{rms}

(3) stability $\pm$ 3 % for 2 hours.

3.3.4 Expected Output Values. The output values shall be consistent with the requirements for normal operation of the Mini-Ranger and MVUE. The expected results are:

(1)

(2)

(3)

3.3.5 Data Collection Methods. Direct measurement of the power characteristics of the R/V ACANIA shall be made using a voltmeter, an osciloscope, and the data recorded in the test observer's log.

3.3.6 Timing Requirements. The power characteristics shall be measured every 15 minutes for a period of two (2) hours.

3.3.7 Degradation. The power characteristics shall remain adequate during the test period.

3.3.8 Casualty Recovery. Power system repairs shall be made by competent maintainance personnel.

3.3.9 Display. No displays shall be generated by this test.

3.4 Operational Check. The operational check of the manpack (MVUE) shall perform normal MVUE startup, operation of the CDU switch functions, CDU input control buttons, and test functions.

3.4.1. Pretest Conditions. The visual inspection test and the power stability test (if required) shall be performed prior to this test. The test shall commence 30 minutes prior to the rise of the first satellite. The test shall take place at a known control point. The MVUE serial number and program identification number shall be recorded.

3.4.2 Test Inputs. The MVUE will be energized and the Equipment Stabilization Period (ESP) noted. The initialization procedures will be executed entering initial time, altitude, position, and satellites desired. The test functions will be executed. Waypoint data shall be entered as shown in Table 3-3.

3.4.3 Expected Accuracies. No error indications shall be received from the tests. Satellite Vehicle (SV) acquisition shall occur when the SV is 10° above the horizon or when the SV rises above an obstruction.

3.4.4 Expected Output Values. For the test functions, the expected series of displays shall appear. For the acquisition status display, the number of satellites shall increase as they appear 10° above the horizon or an obstruction.

3.4.5 Data Collection Methods. The MVUE operator shall observe the correct indications of the CDU. All times, functions executed, display readings, and other observations shall be intered in the test observer's log.

3.4.6 Timing Requirements. Observe acquisition status display of the number of satellites change as successive acquisitions are made.

3.4.7 Degradation. This test should have no effect on system operating capability.

3.4.8 Casualty Recovery. Ensure collection of adequate failure data to determine the cause of the failure, restore the failed item, and restart the test.

3.4.9 Display. MVUE displays shall be as shown in Figure 3-1 for each function used.

TABLE 3-3. WAYPOINT DATA

STATION NAME	LATITUDE	LONGITUDE
Luces Point (101)	36°38'10".524 N	121°55'38".399 W
Point Pinos Lat. Sta. (102)	36°38'06".857 N	121°55'29".105 W
Monterey American Can Co. (202)	36°37'05".210 N	121°54'10".395 W
KMBY Mast (203)	36°36'56".789 N	121°53'54".678 W
Monterey Presidio Monument (214)	36°36'24".782 N	121°53'48".453 W
Monterey SOFAR (106)	36°36'32".177 N	121°53'24".004 W
Monterey County Disc (301)	36°36'32".141 N	121°53'23".998 W
Breakwater Light USE (205)	36°36'30".675 N	121°53'19".060 W
Seaside 4 (108)	36°36'23".446 N	121°51'38".833 W
Del Monte USNPGS Tower (302)	36°35'57".647 N	121°52'32".609 W

3.5 Truth Check. The truth check shall test the accuracy of the Motorola Mini-Ranger III Position Determining System (MRS).

3.5.1 Pretest Conditions. The visual inspection test shall be performed prior to this test. The R/V ACANIA shall be tied up at the Coast Guard pier. The MRS antenna shall be moved to the presurveyed location on the pier. Two Mini-Ranger positions shall be inergized and operational with clear line-of-sight to the R/V ACANIA. The locations of the reference stations shall be entered, in meters, in UTM format with respect to assumed reference point (Table 3-4.).

3.5.2 Test Inputs. The Mini-Ranger shall read both rates simultaneously. Commands shall be entered to extract smooth position data. The MRS magnetic tape shall record data. The tape record shall be printed on the MRS terminal printer. The track plotter shall be initialized and functioning properly.

3.5.3 Expected Accuracies. The required accuracies shall be:

(1) raw range accuracy $\pm$ 3.0 meters for direct range

(2) position accuracy of $\pm$ 1.5 meters.

3.5.4 Expected Output Values. The location and ranges determined by the Mini-Ranger system shall coincide the geographic location of the known, surveyed point.

3.5.5 Data Collection Methods. The Mini-Ranger shall be operated according to its operational manual. The test observer shall record any significant events. MRS Terminal printouts, plotter outputs, and magnetic tape recordings shall be made. The MRS Magnetic tape recordings shall be reduced at NPS. Realtime printouts shall contain time, range-range data and event marks. Post-processed printouts shall contain time, X-Y data (UTM coordinates) and event marks.

3.5.6 Timing Requirements. Perform data readout overy 20 seconds for a period of 30 minutes. Print out the MRS magnetic tape record on the MRS terminal for 5 minutes.

3.5.7 Degradation. This test should have no effect on system operating capability.

3.5.8 Casualty Recovery. Mini-Ranger III system repairs shall be made by

TABLE 3-4. REFERENCE POINTS (WGS 72)

STATION NAME	LATITUDE/LONGITUDE	NORTHINGS/EASTINGS
Nail	36°36'31".5279 N	4052042.934 N
	121°53'29".2450 W	599138.621 E
Mussel	36°37'17".7244 N	4053453.207 N
	121°54'15".7188 W	597967.837 E
Monterey Bay 4	36°37'30".7035 N	4053917.206 N
	121°50'35".8133 W	603425.230 E
Luces Point	36°38'10".0954 N	4055042.670 N
	121°55'42".4926 W	595794.472 E
Monterey Co.	36°36'31".7159 N	4052049.059 N
	121°53'28".0870 W	599167.323 E
USE MON	36°36'04".2620 N	4051216.957 N
	121°52'39".9914 W	600372.042 E

contractor personnel.

3.5.9 Display. Data output shall conisit of range readings from the reference stations printed out every 10 seconds on the central terminal.

3.6 Static Technical Performance . The static technical performance test shall exercise all MVUE operating functions (Table 3-5) and determine performance characteristics (Table 3-1).

3.6.1 Pretest Conditions. The visual inspection, power stability (if required) and operational check tests shall be performed prior to this test. The MVUE shall be located at test control station. The test observer shall observe MVUE operation to verify pretest performance data.

3.6.2 Test Inputs. The cable connecting the antenna shall be removed for 5, 10, and 30 seconds and reconnected to measure signal reacquisition. The CDU shall be placed in AUTO for varying times and restored to measure the AUTO update period and in STBY position for varying times and restored to measure the Time-To- Subsequent-Fix (TTSF) interval. The manpack will be deenergized momentarily to determine quipment stabilization period (ESP) and time-to-first-fix (TTFF) when the MVUE is initialized with inaccurate position data. The MVUE will be initialized as necessary. The MVUE CDU shall be used to exercise/observe all MVUE operating functions. Data inputs via the CDU shall be as required for each specific function. Operation at each function shall include function select, data entry, data readout, and data change.

3.6.3 Expected Accuracies. The required accuracies are shown in Table 3-1.

3.6.4 Expected Output Values. The MVUE shall show the correct position waypoints at all times. Removal of the manpack antenna cable for less than 10 seconds will cause a reacquisition time of 30 seconds, while removal for longer that 10 seconds will cause a reacquisition time of 60 seconds. Entering incorrect position data during initialization shall increase TTFF.

3.6.5 Data Collection Methods. All times, functions executed, display readings and other observed results shall be entered in the test observer's log.

3.6.6 Timing Requirements. This test shall run until 15 minutes after the last satellite sets. The MVUE functions shall be exercised every 15 to 30 minutes during the test periods.

3.6.7 Degradation. The MVUE should lose the SV signals after removing the

TABLE 3-5. STATIC TECHNICAL PERFORMANCE MVUE FUNCTIONS

LAT	Latitude, longitude, datum
ALT	Altitude, CEP, PE, number of satellites
GRD	Zone, band, datum, northing, easting
TIM	GPS or ZULU: year, day, hour, minute, second
RNG	Station number, meters, degrees
SV	Satellite constellation selection
OPT OP2	User options (Ephemeris update, user dynamics, etc.)
BIT	Built-in-test authorization

antenna cabling.

3.6.8 Casualty Recovery. The MVUE should automatically recover from the loss of SV signals. If the MVUE does not automatically reacquire the SV, the search mode will be entered until the SV is reacquired. If a casualty occurs, ensure collection of adequate failure data to determine the cause of failure, restore the failure, and restart the test.

3.6.9 Display. MVUE displays shall be as shown in Figure 3-1 for each function used.

3.7 Beach Test. The Beach Test shall be run on two non-consecutive nights, preferably at the beginning and end of the test period. The Beach Test will observe how well the MVUE static readouts compare to the latitude and longitude of a known control station as shown in Figure 3.5.

3.7.1 Pretest Conditions. The visual inspection, power stability (if required), operational check, and static technical performance shall be run prior to this test. The test observer shall observe MVUE operation to verify pretest performance data. The antenna shall be set up over the station. The test shall be performed during SV availability.

3.7.2 Test Inputs. The MVUE shall be used to ovserve latitude and longitude for the duration of SV availability.

3.7.3 Expected Accuracies. The required accuracies are shown in Table 3-1.

3.7.4 Expected Output Values. The MVUE shall show the correct location of the station at all times.

3.7.5 Data Collection Methods. All times, functions executed, display readings, and other observed data shall be entered in the Test Observer's log.

3.7.6 Timing Requirements. The MVUE latitude and longitude shall be ovserved every 30 seconds for the duration of the SV availability.

3.7.7 Degradation. This test should have no effect on system operating capability.

3.7.8 Casualty Recovery. Ensure collection of adequate failure data to determine the cause of the failure, restore the failed item, and restart the test.

3.7.9 Display. MVUE displays shall be as shown in Figure 3-1 for each function used.

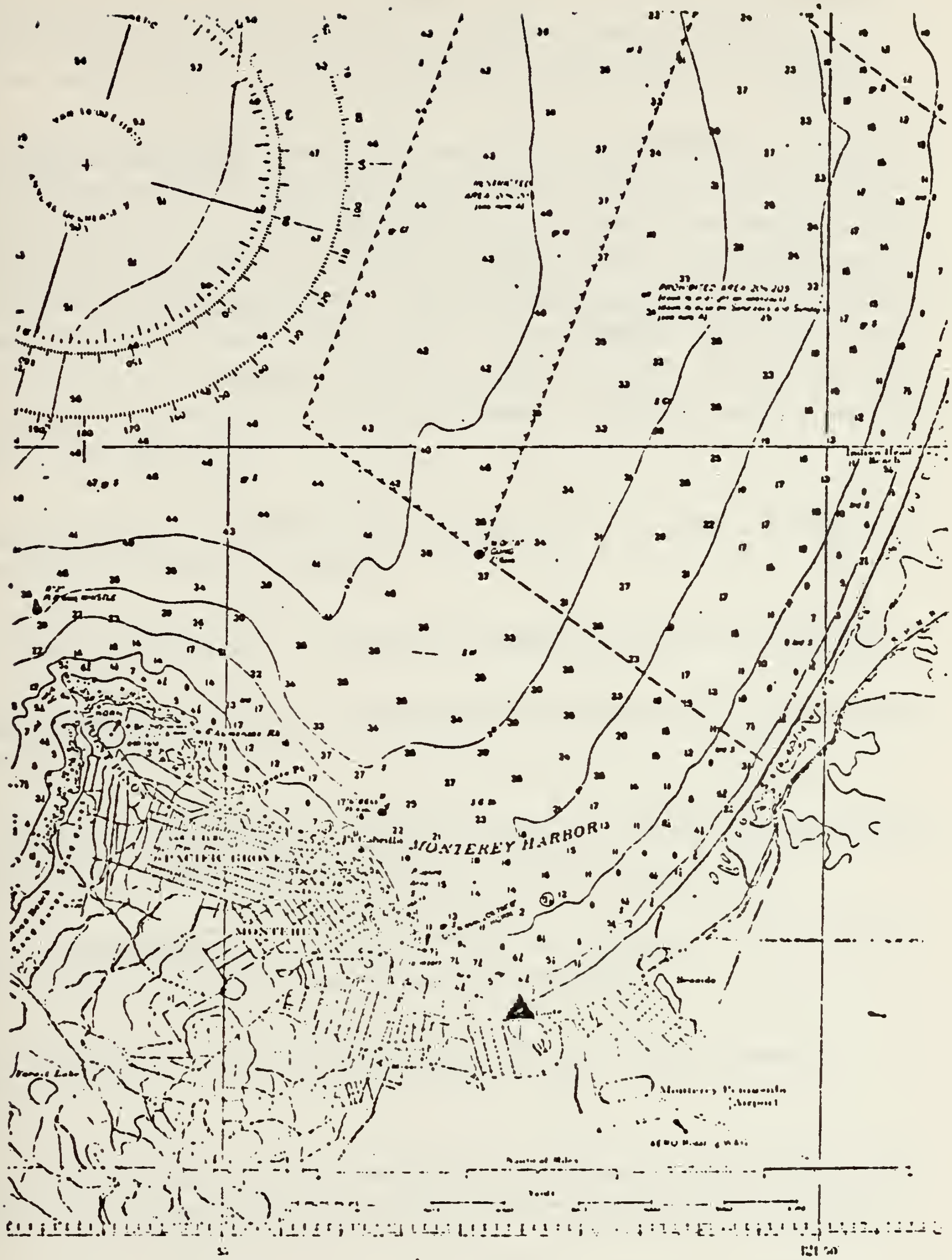


FIGURE 3-5. BEACH TEST LOCATION

3.8 Pier Test. The Pier Test shall observe how well the MVUE operates under low-dynamic conditions. It will compare the MVUE readouts to Mini-Ranger positions when the Mvue is installed on the R/V ACANIA tied up to the pier.

3.8.1 Pretest Conditions. The visual inspection, power stability (if required), truth check, operational check, and static technical performance test shall be run prior to this test. The R/V ACANIA shall be located at her normal berthing location on the Coast Guard Pier. The test observer shall observe MVUE operation to verify pertest performance data. Two Mini-Ranger positions shall be energized and operational with clear line-of-sight to the R/V ACANIA. The two positions shall be entered into the MVUE as reference points as in Figure 3-6. All reference stations shall be defined in UTM coordinates. The tests shall be performed during the SV availability.

3.8.2 Test Inputs. The MVUE shall be used to observe latitude and longitude for the duration of SV availability.

3.8.3 Expected Accuracies. The required accuracies are shown in Table 3-1.

3.8.4 Expected Output Values. The MVUE shall show the correct location of the station at all times.

3.8.5 Data Collection Methods. All times, functions executed, display readings, and other observed data shall be entered in the Test Observer's log.

3.8.6 Timing Requirements. The MVUE latitude and longitude shall be observed every 15 seconds for the duration of the SV availability.

3.8.7 Degradation. This test should have no effect of system operation capability.

3.8.8 Casualty Recovery. Ensure collection of adequate failure data to determine the cause of the failure, restore the failed item, and restart the test.

3.8.9 Display. MVUE displays shall be as shown in Figure 3-1 for each function used.

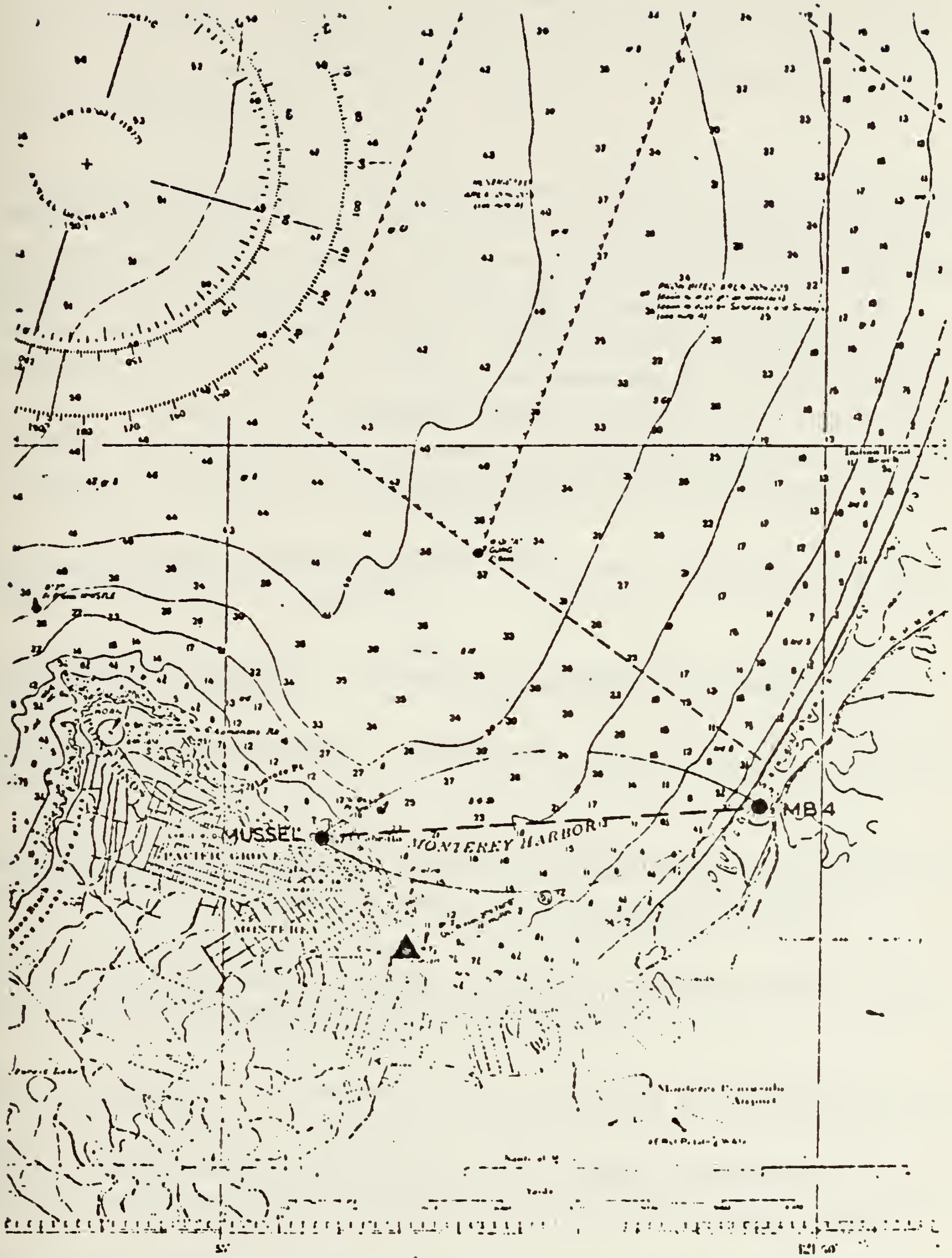


FIGURE 3-6. PIER TEST LOCATION

3.9 Anchor Test. The Anchor Test shall observe how well the MVUE operates under medium-dynamic conditions. It will compare the MVUE readouts to Mini-Ranger positions when the MVUE is installed on the R/V ACANIA swinging at anchor in Monterey Bay.

3.9.1 Pretest Conditions. The visual inspection, power stability (if required), truth check, operational check and static technical performance tests shall be run prior to this test. The R/V ACANIA shall be anchored off the firing range buoy in suffficiently deep water to allow her to swing fully. The test observer shall observe MVUE operation to verify pretest performance data. Two Mini-Ranger stations shall be energized and operational with clear line-of-sight to the R/V ACANIA. The two positions shall be entered into the MVUE and reference points as in Figure 3-7. All reference stations shall be defined in UTM coordinates. The test shall be performed during the SV availability.

3.9.2 Test Inputs. The MVUE shall be used to observe latitude and longitude for the duration of SV availability.

3.9.3 Expected Accuracies. The required accuracies are shown in Table 3-1.

3.9.4 Expected Output Values. The MVUE shall show the correct location of the ship at all times.

3.9.5 Data Collection Methods. All times, functions executed, display readings, and other observed data shall be entered in the Test Observer's log.

3.9.6 Timing Requirements. The MVUE latitude and longitude shall be observed every 30 seconds for the duration of SV availability.

3.9.7 Degradation. This test should have no effect on system operating capability.

3.9.8 Casualty Recovery. Ensure collection of adequate failure data to determine the cause of the failure, restore the failed item and restart the test.

3.9.9 Display. MVUE displays shall be as shown in Figure 3-1 for each function used.

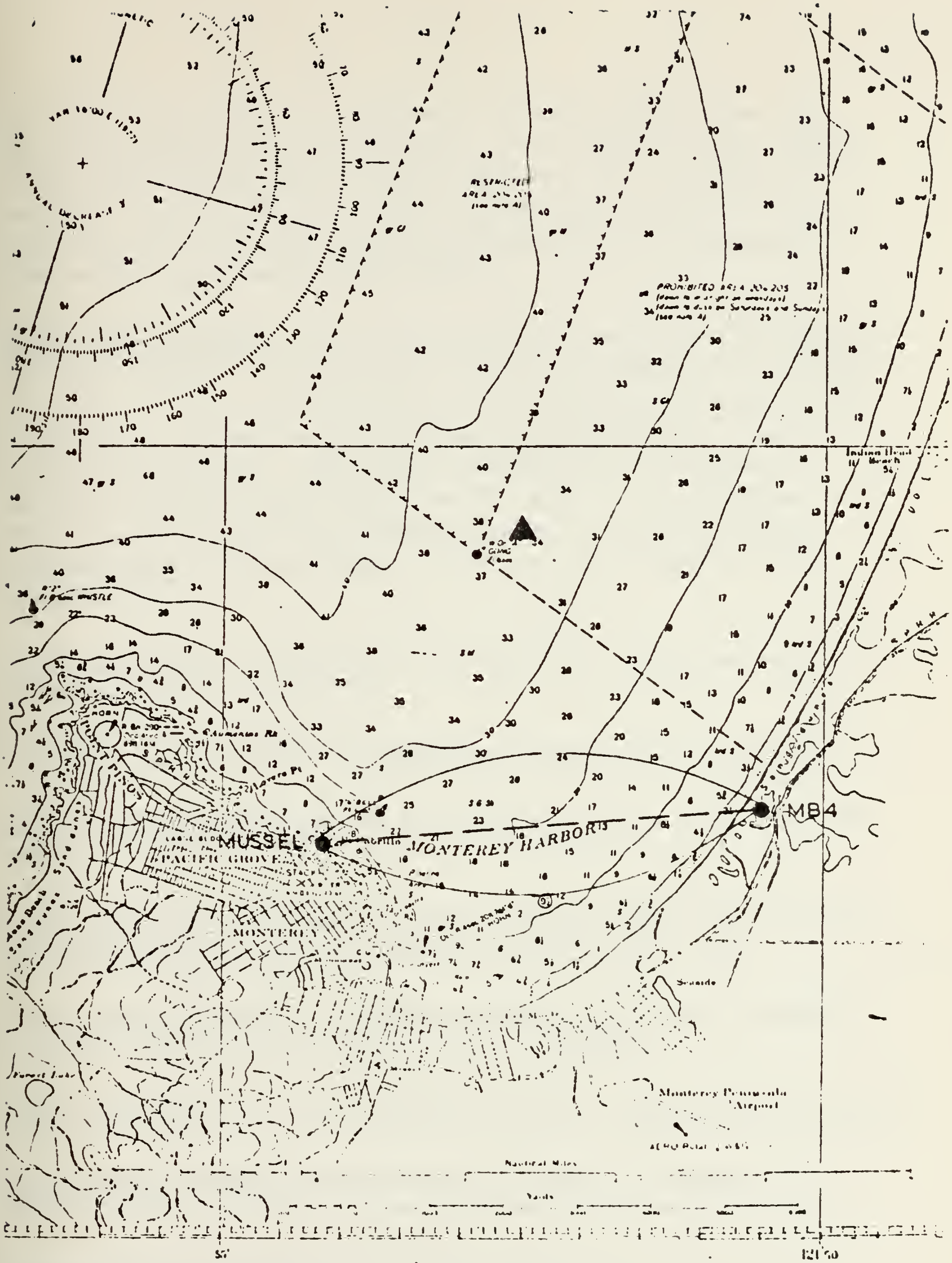


FIGURE 3-7. ANCHOR TEST LOCATION

3.10 High Dynamics Test. The High Dynamics Test shall observe how well the MVUE operates under high dynamic conditions. It will compare the MVUE readouts to Mini-Ranger positions when the MVUE is installed on the R/V ACANIA which is running a 2.5 nautical mile line, making a Williamson turn (180^{0}) and returning over the same track. This test will be conducted twice with the two sets of lines running at right angles to each other.

3.10.1 Pretest Conditions. The visual inspection, power stability (if required), truth check, operational check, and static technical performance tests shall be run prior to this test. The R/V ACANIA shall be operating in the area delineated in Figure 3-8. The Test Observer shall observe the MVUE operation to verify pretest performance data. Two Mini-Ranger stations shall be energized and operational with clear line-of-sight to the R/V ACANIA. The two positions shall be entered into the MVUE as reference points. All reference stations shall be defined in UTM coordinates. The test shall be performed during the SV availability.

3.10.2 Test Inputs. The MVUE shall be used to observe latitude and longitude for the duration of SV availability.

3.10.3 Expected Accuracies. The required accuracies are shown in Table 3-1.

3.10.4 Expected Output Values. The MVUE shall show the correct location of the ship at all times.

3.10.5 Data Collection Methods. All times, functions executed, display readings and other observed data shall be entered in the Test Observer's log.

3.10.6 Timing Requirements. The MVUE latitude and longitude shall be observed every 15 seconds while the lines and the turns are being run.

3.10.7 Degradation. This test should have no effect on system operating capability.

3.10.8 Casualty Recovery. Ensure collection of adequate failure data to determine the cause of the failure, restore the failed item and restart the test.

3.10.9 Display. MVUE displays shall be as shown in Figure 3-1 for each function used.

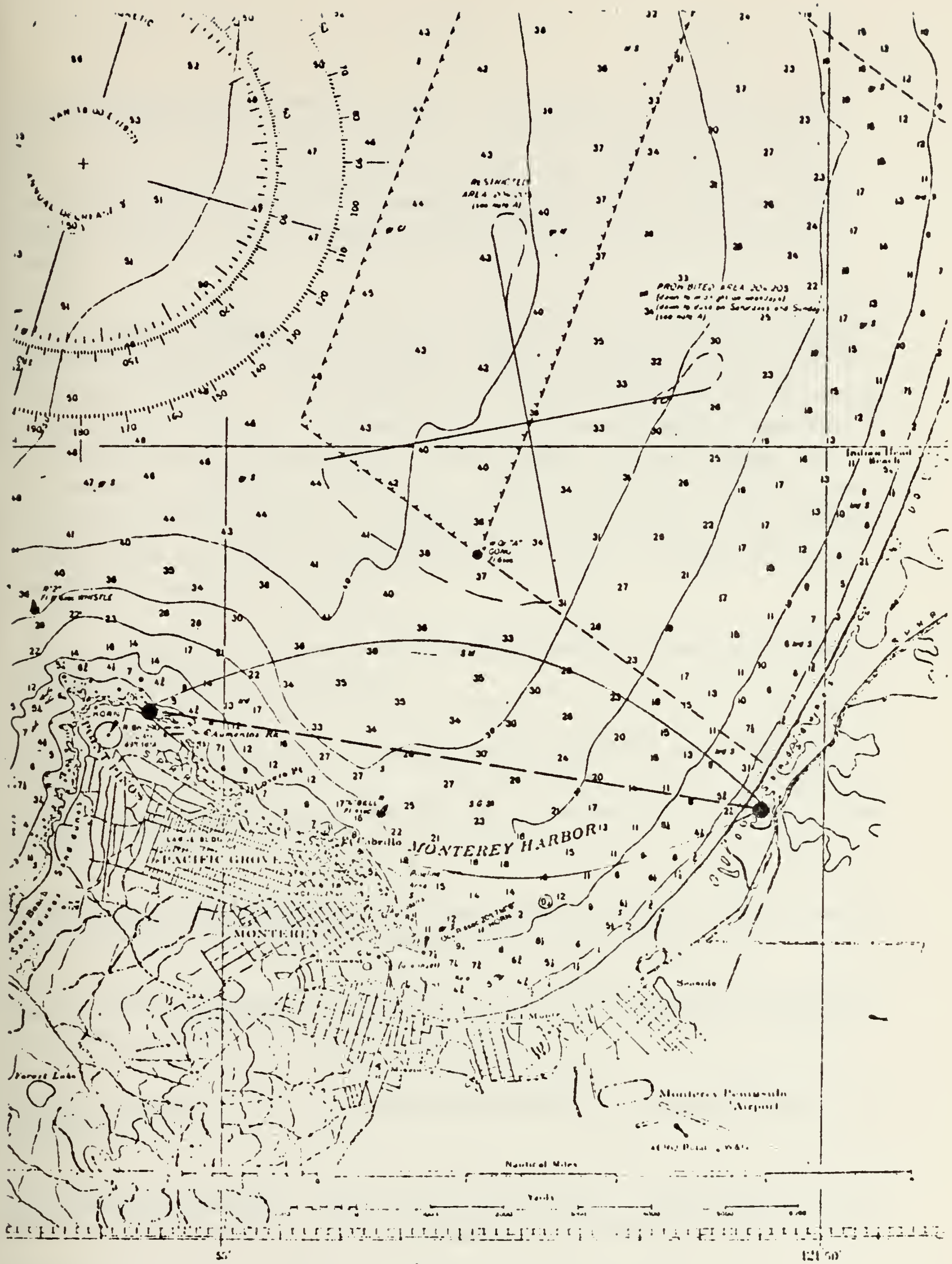


FIGURE 3-8. HIGH DYNAMICS TEST LOCATION

3.11 Survey Scenario. The Survey Scenario shall observe how well the MVUE operates under actual survey conditions. The survey scenario will involve three separate parts: a circle test, a 5-knot lattice and a 9-knot lattice. These tests will compare the MVUE readouts to Mini-Ranger positions when the MVUE is installed on the R/V ACANIA and operating as a survey vessel would operate.

3.11.1 Pretest Conditions. The visual inspection, power stability (if required), truth check, operational check and static technical performance tests shall be run prior to this test. The R/V ACANIA will be operating in the area delineated in Figures 3-9A and 3-9B. The Test Observer shall observe the MVUE operation to verify pretest performance data. Two Mini-Ranger reference stations shall be energized and operational with clear line-of-sight to the R/V ACANIA. The two positions shall be entered into the MVUE as reference points. All reference stations shall be defined in UTM coordinates for the MRS. The test shall be performed during the SV availability.

3.11.2 Test Inputs. the MVUE shall be used to observe latitude and longitude for the duration of SV availability.

3.11.3 Expected Accuracies. The required accuracies are shown in Table 3.1.

3.11.4 Expected Output Values. The MVUE shall show the correct location of the ship at all times.

3.11.5 Data Collection Methods. All times, functions executed, display readings, and other observed data shall be entered in the Test Observer's log.

3.11.6 Timing Requirements. The MVUE latitude and longitude shall be observed every 15 seconds while the lines are being run.

3.11.7 Degradation. This test should have no effect on system operating capability.

3.11.8 Casualty Recovery. Ensure collection of adequate failure data to ensure the cause of the failure, restore the failed item and restart the test.

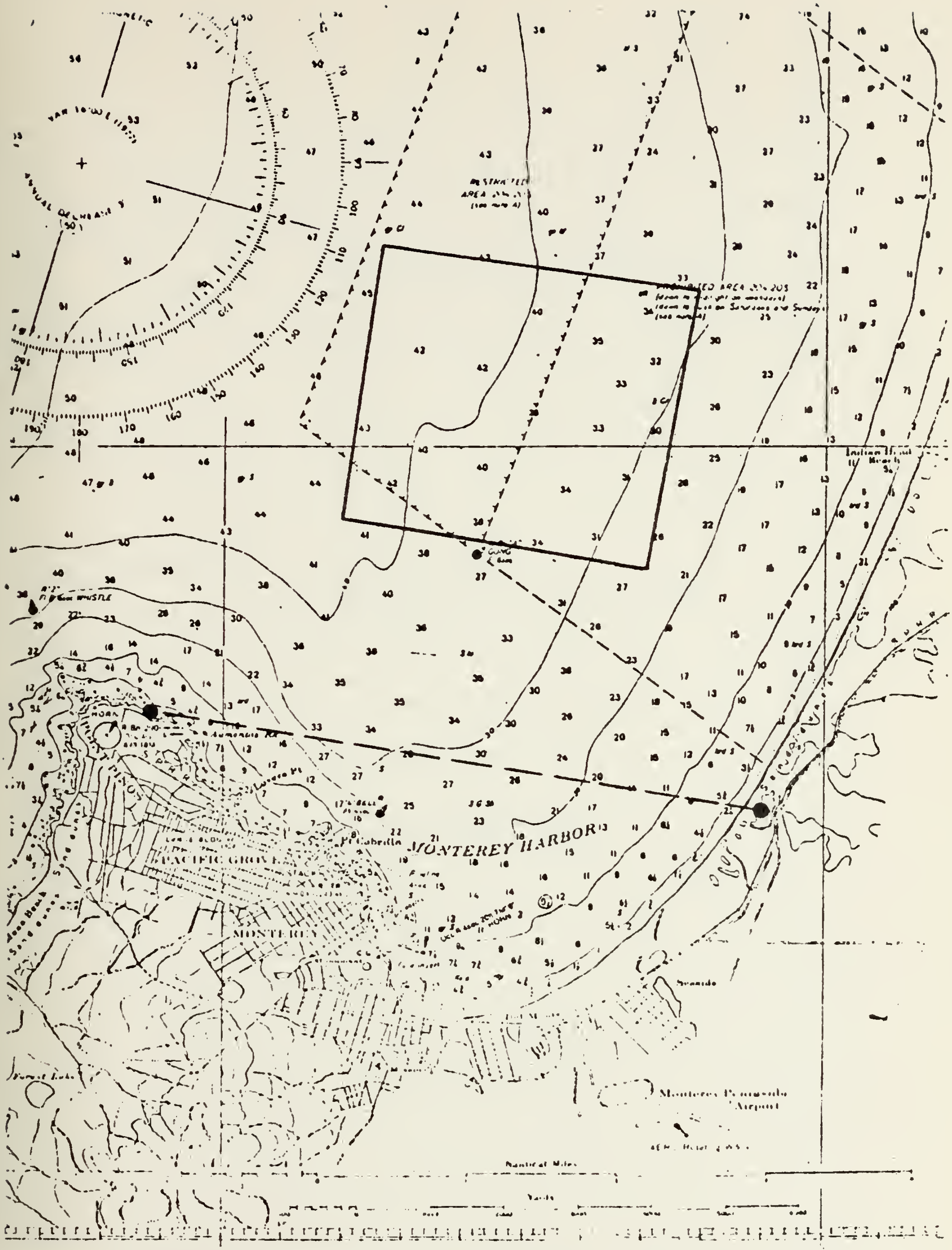


FIGURE 3-9A. SURVEY SCENARIO: CIRCLE & NINE KNOT TEST

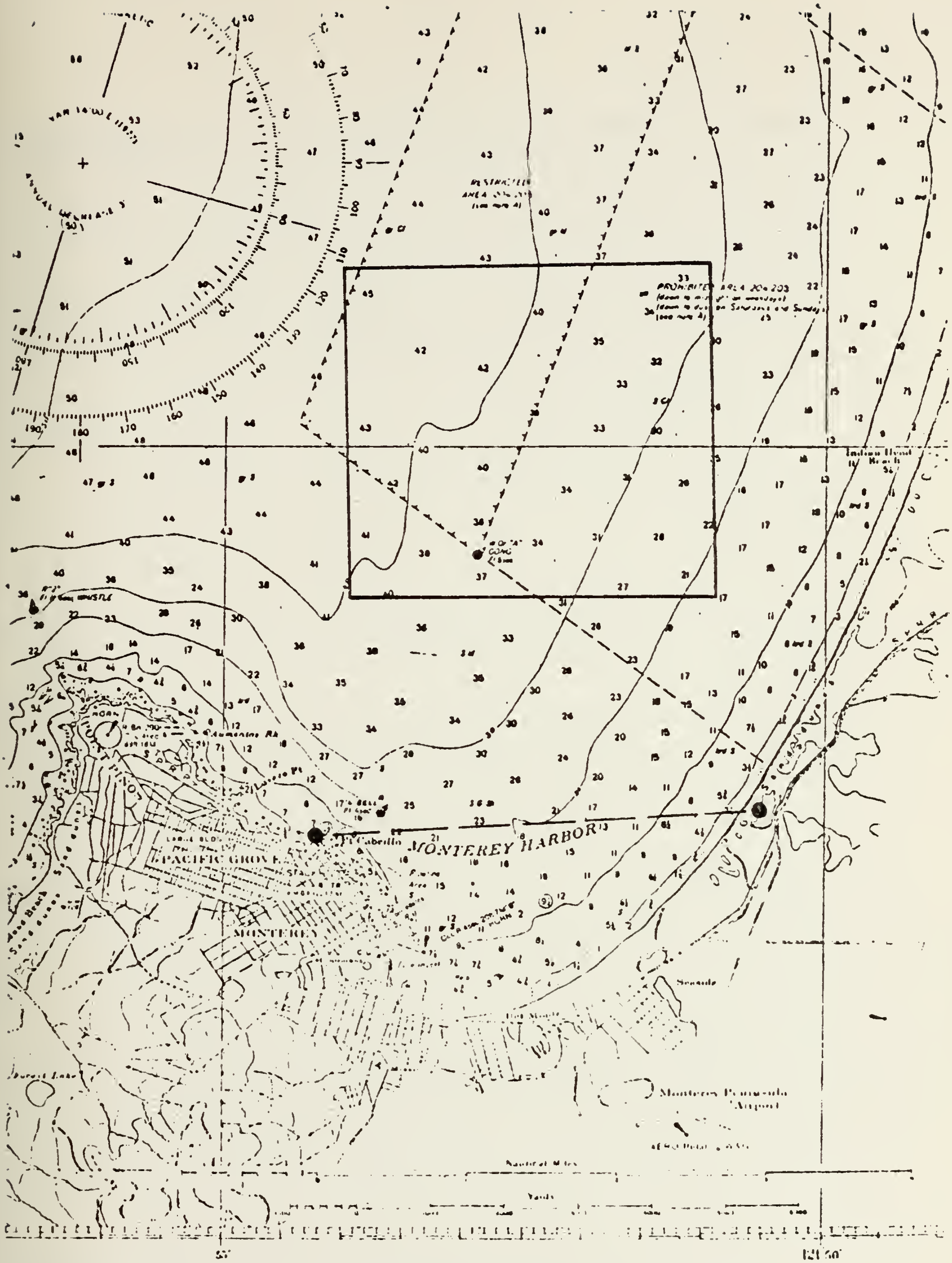


FIGURE 3-9B. SURVEY SCENARIO: FIVE KNOT TEST

3.11.9 Display. MVUE displays shall be as shown in Figure 3-1 for each function used.

SECTION IV

TEST ORGANIZATION AND MANAGEMENT REQUIREMENTS

4.1 General Management Requirements. The GPS/Hydrographic Applications Test is being developed by P. Dunn and J. Rees to partially satisfy thesis requirements of the Naval Postgraduate School. They are also responsible for data analysis and test evaluation procedures. Associated activities and their responsibilities are delineated in the following paragraphs.

4.2 Naval Postgraduate School (NPS). The Naval Postgraduate School's responsibilities are:

(1) Operation and maintainance of R/V ACANIA.

(2) Logistical support, i.e., contracting, shipping, and monitoring of funds

(3) Technical advice and support

4.3 Space and Missile System Organization (SAMSO). SAMSO is responsible for exercising managerial control over government provided equipment, i.e., MVUE.

4.4 TEXAS INSTRUMENTS, INC. (TI). As the development contractors for the GPS Manpack/Vehicular User Equipment, Texas Instrument will:

(1) Perform pre- and post-mission MVUE checkout.

(2) Provide operation and maintainance for the hardware.

4.5 Others. Other support supplied by the following groups or agencies:

(1) Defense Mapping Agency (DMA) supplied charts, geodetic positioning transformations, funding and technical advice.

(2) Naval Oceanographic Office (NAVO) supplied a Del Norte Trisponder, funding, and technical advice.

(3) Naval Oceans Systems Center (NOSC) supplied hands-on exposure prior to test, technical advice, and substantial written material.

(4) MOTEROLA supplied MRS III Positioning Determining System and technical support.

(5) National Oceanographic and Atmospheric Agency (NOAA) supplied charts.

SECTION V

PERSONNEL REQUIREMENTS

5.1 Test Operations. Table 5-1 list the test stations to be manned during the test aboard the R/V ACANIA.

5.2 Test Station Manning. Table 5-2 provides a comprehensive list of personnel required for conduct of the tests.

5.3 Personnel Availability. Figure 5-1 shows the requirements for availability of personnel for each test.

TABLE 5-1. TEST STATIONS

SITE	STATION ID	STATION FUNCTION
Shore station	Shore Party	Maintain shore equipment
ACANIA	Test Director/Observer	Direct tests and log significant events
ACANIA	MVUE Operator	Operates MVUE
ACANIA	Master	Directs ship's operation
ACANIA	Timer	Calls marks for Positioning, altitude, satellites, etc.
ACANIA	Recorder	Logs MVUE data, event marks, and comments
ACANIA	MRS Operator	Operates MRS III
ACANIA	Fathometer Operator	Records event marks and times on fathometer

TABLE 5-2. TEST MANNING

ABREU, Francisco, LCDR, Portuguese Navy; FO
BLOSS, Wally, LT, USN; EE
BRONSINK, Sherman, LT, USN; MO, MRO, R, SP
BROWN, Gene, CIV, NAVO; SP, R
BROWN, Mary, CIV; MO, R
BURGESS, Leslie, LT, USN; MO, MRO
CANNADY, Charles, LCDR,USN; MRO
DUNN, Penny, CIV, NAVO, TD/TO
EATON, Patricia, CIV, DMA; MRO
FARIA, Isabel, CIV; FO
FARIA, Luis, LTJG, Portuguese Navy; T, MO, R
HANNA, James, LT, USN; R
HANSON, Walter, LT, CG; SP
HOFFMAN, Richard, LT, USN; FO
JORDAN, David, CIV, TI; TR
JOY, Richard, CIV, DMA; MRO, SP
KAPLAN, Ali, LTJG, Turkish Navy; SP
LIETH, Dudley, LCDR, USN; T
MILLS, Gerald, LCDR, NOAA; T, MO
MOULAISON, Robert, CIV, Westinghouse; SP
NEWELL, Virginia, LT, NOAA; MO,T,R,MOR, SP
NORTRUP, Donald, CDR, NOAA; T, MO
PERRIN, Kenneth, LT, NOAA; MO,FO, R, T
REES, Anna, CIV; SP
REES, John, CIV, DMA; TD/TO
SHOOK, Jenny, CIV; SP
SHOOK, Ricky, LT, USN; SP
WINTER, Donald, LCDR, NOAA; SP

EE - Electrical Enginneer
FO - Fathometer Operator
MRO - Mini-Ranger Operator
MO - MVUE Operator
R - Recorder
SP - Shore Party
T - Timer
TD/TO - Test Director/Observer
TR - Technical Representative

FIGURE 5-1. PERSONNEL AVAILABILITY REQUIREMENTS

	Visual Inspection	Power Stability	Operational Check	Truth Check	Static Tech. Perform.	Beach Test	Pier Test	Anchor Test	High-Dynamics Test	Survey Scenario
Shore Party				x			x	-	-	x
Test Director	x	-	-	-	-	-	-	-	-	x
Test Observer	x	-	-	-	-	-	-	-	-	x
Master				x			x	-	-	x
MVUE Operator	x	-	x		x	-	-	-	-	x
Timer						x	-	-	-	x
Recorder							x	-	-	x
MRS Operator				x			x	-	-	x
Fathometer Operator								x	-	x
Electrical Engineer		x								
Tech. Representative	x	-	-	-	-	-	-	-	-	x

SECTION VI

HARDWARE AND SOFTWARE REQUIREMENTS

6.1 R/V ACANIA Installation. Hardware for the R/V ACANIA platform includes the manpack, power filter, CDU and antenna. Figure 6-1 shows the setup of the manpack (MVUE) inside the ACANIA.

6.2 Test Support Equipment. Equipment required for test support includes a regulated power supply.

6.3 Mini-Ranger III System. The Moterola Mini-Ranger III Positioning Determining System (MRS III) is used to accurately determine the position of the R/V ACANIA. The position of the ship is determined with respect to the two reference stations both of which are located at known fixed points. The MRS, operating on the basic principle of pulse radar, uses a transmitter located on the ACANIA and transponders located at two stations. The elapsed time between transmitted interrogations produced by the MRS III Transmitter and the reply received from each transponder is used as the basis for determining the range to each transponder. This range information, displayed by the MRS III together with the known location of each trnsponder, can be trilaterated to provide a position of the ACANIA..

The standard MRS III operates at line-of-sight ranges up to 20 nautical miles (37 Km) and with appropriate calibration, the probable range measurement accuracy is better than 3 meters (10 feet). A unique coding system is employed in the MRS to minimize false range readings caused by radar interference and to provide selective reference station interrogation.

6.3.1 MRS Installation. The MRS III transmitter with antenna is installed onboard the R/V ACANIA and operates on +28 VDC power supplied by the range console. The MRS Transpnder stations are to be positioned over sites whose locations provide the best geometry for that day's test. Transponder stations shall be set up and dismantled each night for security reasons and batteries shall be recharged as necessary to provide sufficient power for the duration of the test.

6.3.2 MRS Data Extraction. The MRS shall output data in three forms: terminal printout, plotter printout, and magnetic tape. the MRS collects data

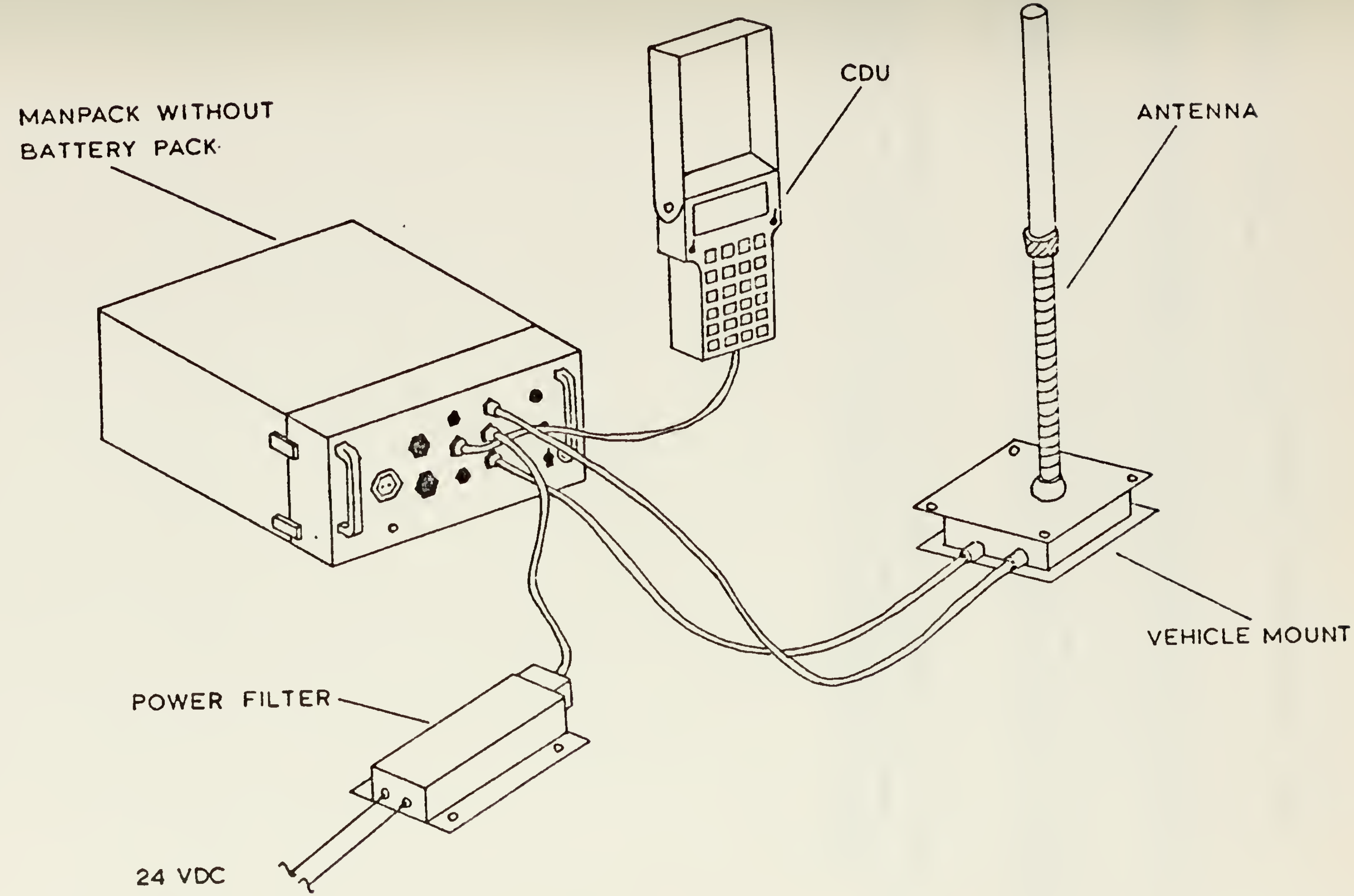


FIGURE 6-1. VEHICLE INSTALLATION

and performs calculations using the Universal Transverse Mercator (UTM) coordinate system shown in Table 3-3.

6.3.2.1 MRS Terminal Printout. The MRS terminal printer can print out, on deamnd, ranges or UTM grid coordinates (x,y), time and event marks.

6.3.2.2 MRS Plotter Output. The MRS plotter will produce a plot of relative position with event marks either once a minute (automatic mode) or on demand (manual mode).

6.3.2.3 MRS Magnetic Tape. The MRS will output to magnetic tape UTM grid positions, time and event marks at the rate of once every two seconds. The magnetic tape information will be processed at NPS and printouts produced in UTM positions.

SECTION VII

SUPPORT FACILITIES

7.1 R/V ACANIA Support. The R/V ACANIA will act as primary test vehicle for the tests and will provide all required ship's operations in the Monterey Bay operating area.

SECTION VIII

SCHEDULE

8.1 General Schedule Requirements. This section provides the general schedule of events for performance of the GPS/Hydrographic field test operations. Objectives of the schedule provided are to set a testing period (30 April-6 May 1980) to accumulate performance data. Table 8-1 provides the general chronology of major events. Figures 8-1 and 8-2 provide the schedule of satellite signal availability in the Monterey Bay area. The following paragraphs provide a more detailed schedule of the specific test operations.

8.2 Test Operations. Preliminary on-site testing the Mini-Ranger III system will occur from 17 April-28 April 1980. Tests with the MVUE will commence upon completion of system installation, about 29 April 1980. Table 8-2 lists the significant operations and associated major resource requirements. The dominating factor in the schedule is the daily 10 hour (approximate) satellite signal availability window (of which 4 to 5 hours occurs before ephemeris update) for position fixing. In addition, only about three hours of the satellite availability period after the updates provide the four satellite coverage required for the standard three-dimensional position fixing mode of operation of the GPS equipment. In the event that satellite availability is limited to three satellites, the equipment automatically goes to altitude hold mode.

TABLE 8-1. MASTER TEST CHRONOLOGY

EVENT	DATE
Beach Test I	29 April 1980
Pier Test	30 April 1980
Anchor Test	1 May 1980
High-Dynamics Test	2 May 1980
Survey Scenario	
Circle Test	3 May 1980
5-knot Lattice	4 May 1980
9-knot Lattice	5 May 1980
Beach Test II	6 May 1980

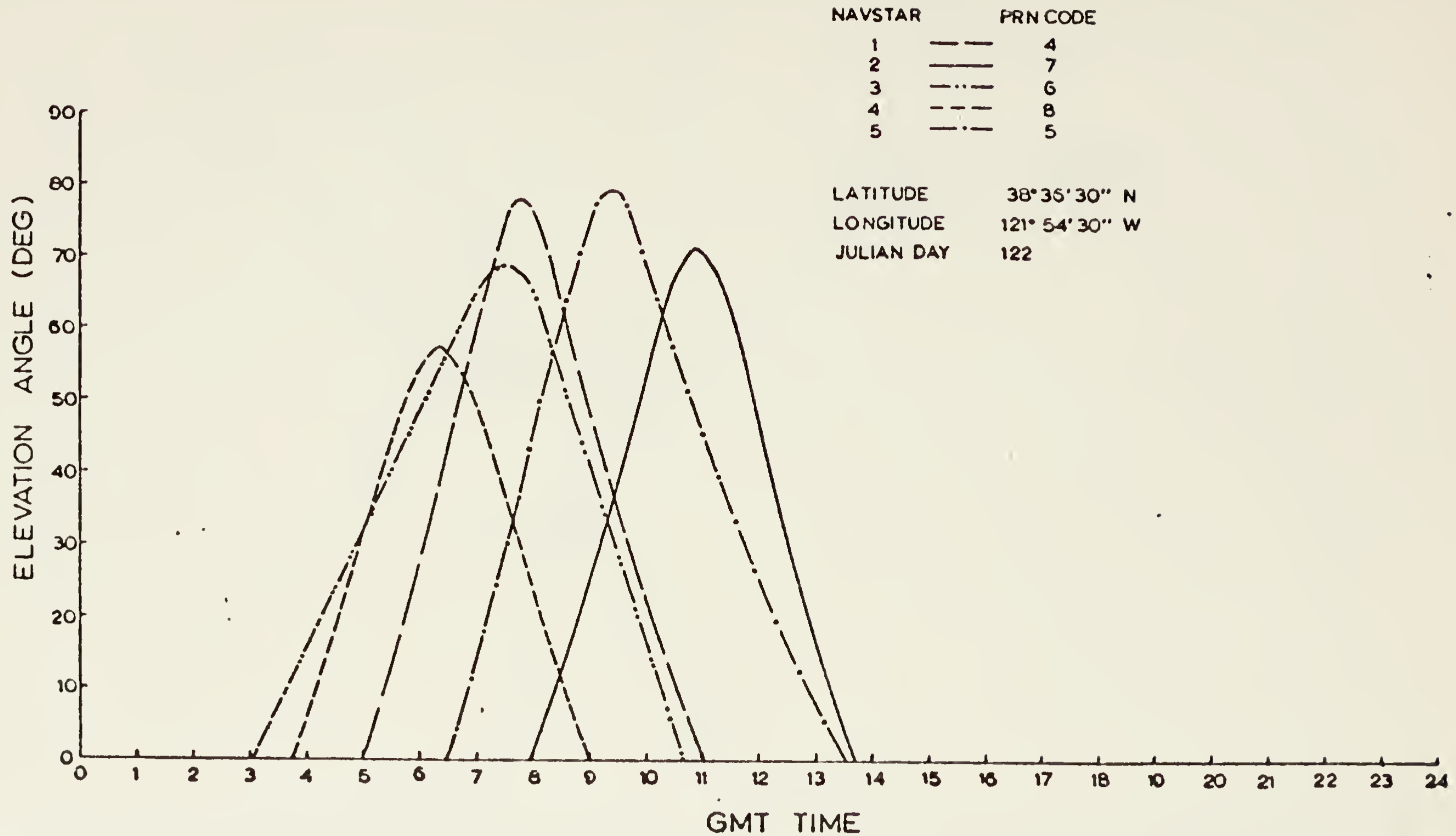


FIGURE 8-1. ELEVATION ANGLES

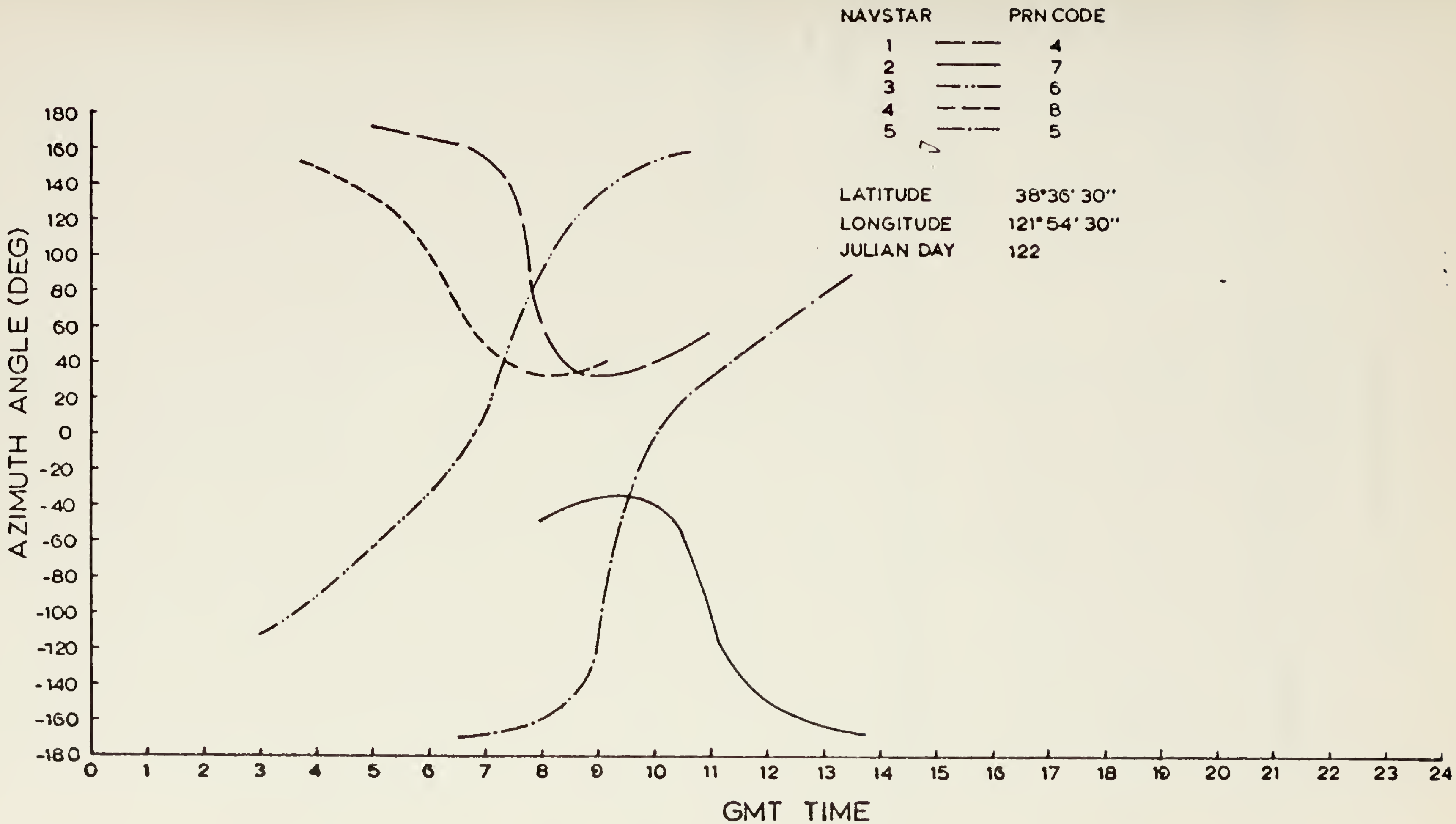


FIGURE 8-2. AZIMUTH ANGLES

TABLE 8-2. TEST OPERATIONS AND MAJOR RESOURCE SCHEDULING

TEST OPERATIONS	SV SIGNALS	MRS III	LOCATION[1]
Visual Inspection			A
Power Stability			A
Operational Check	X		A
Truth Check		X	P,H,S
Static Technical Perform.	X		A
Beach Test	X		B
Pier Test	X	X	P
Anchor Test	X	X	H
High-Dynamics Test	X	X	S
Survey Scenario	X	X	S

1. A - All locations
   B - Beach
   P - Pier
   H - Bay
   S - Survey scenario

SECTION IX

TEST EVALUATION

9.1 Data Collection. Primary information currently identified for collection is of two general types:

(1) Type I - The precision range data from the Mini-Ranger III tracking system and the positions generated by the MVUE.

(2) Type II - Logs, charts, and data sheets prepared by the test participants.

Type I data is of a precision and diagnostic nature, whereas Type II describes the general environment, events, and observations during the tests.

9.2 Test Analysis and Review.

9.2.1 Type I Data. Detailed analysis of Type I data woll be provided following the completion of the tests. Reduction and compilation of range data and statistical analysis shall be done by P. Dunn and J. Rees.

9.2.2 Type II Data. Type II data will be evaluated and incorporated into Type I data where it has bearing.

9.3 Test Reports. Following processing of the test data, the Test Report will be generated as part of the thesis requirements.

APPENDIX F: COORDINATE SHIFT AND RANGE CORRECTION APPLIED TO DAY 126, LINE 6

Offset statistics with range and coordinate shift corrections for 18 points along track line 6 for day 126.

F = Empirical Density Function

$$F_n (z) = \frac{1}{nB(n)} \sum_{i=1}^{n} w \; ((x_i - z)/B(n))$$

$W (z) = 0 \quad \text{if } z > i$

$\qquad\quad 1 \quad \text{if } 1-z \quad \text{otherwise}$

m = mean

n = number of data points

B (n) = Range/ $\sqrt{n}$

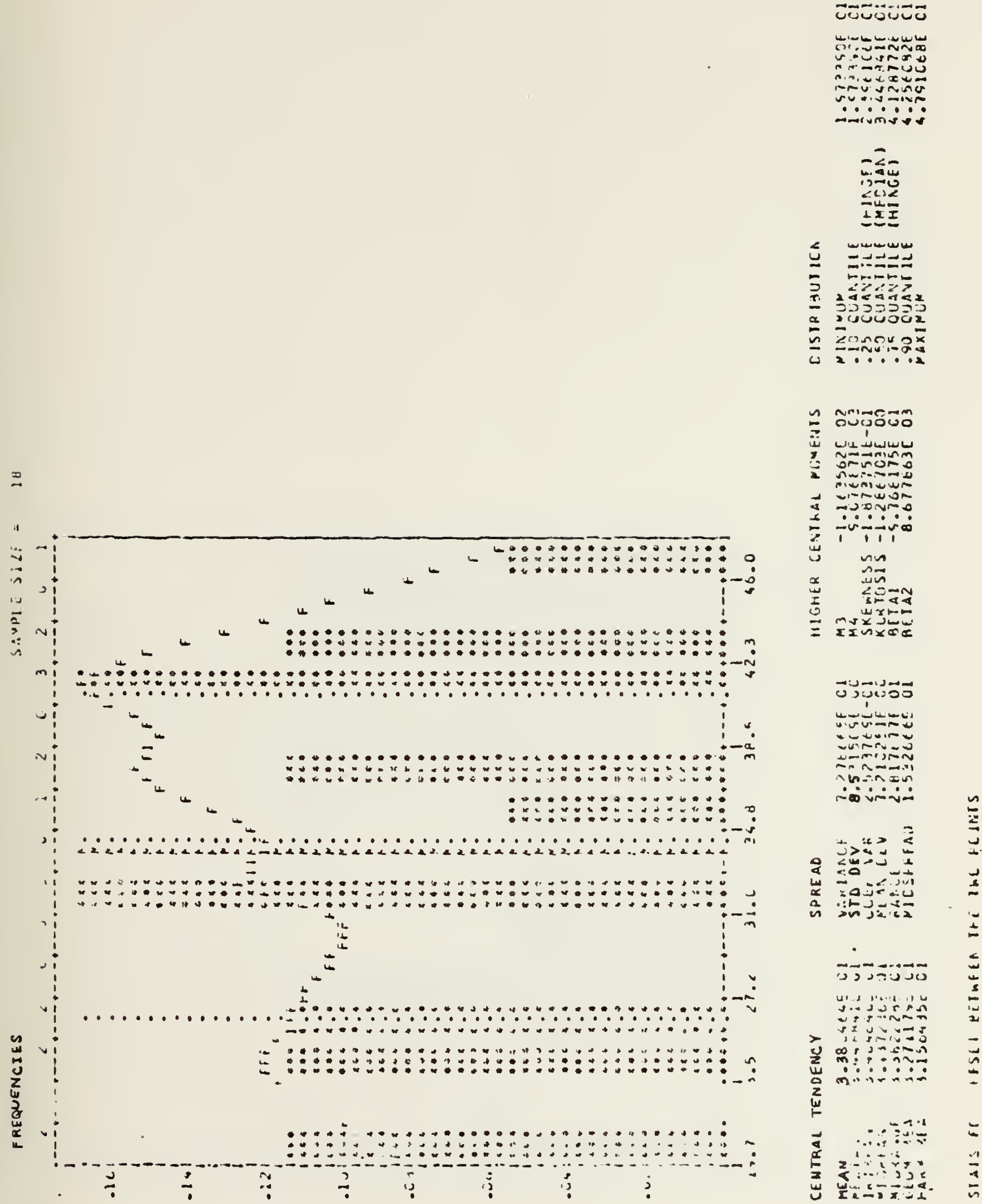


Figure F-1. Original Data, Day 126 Line 6

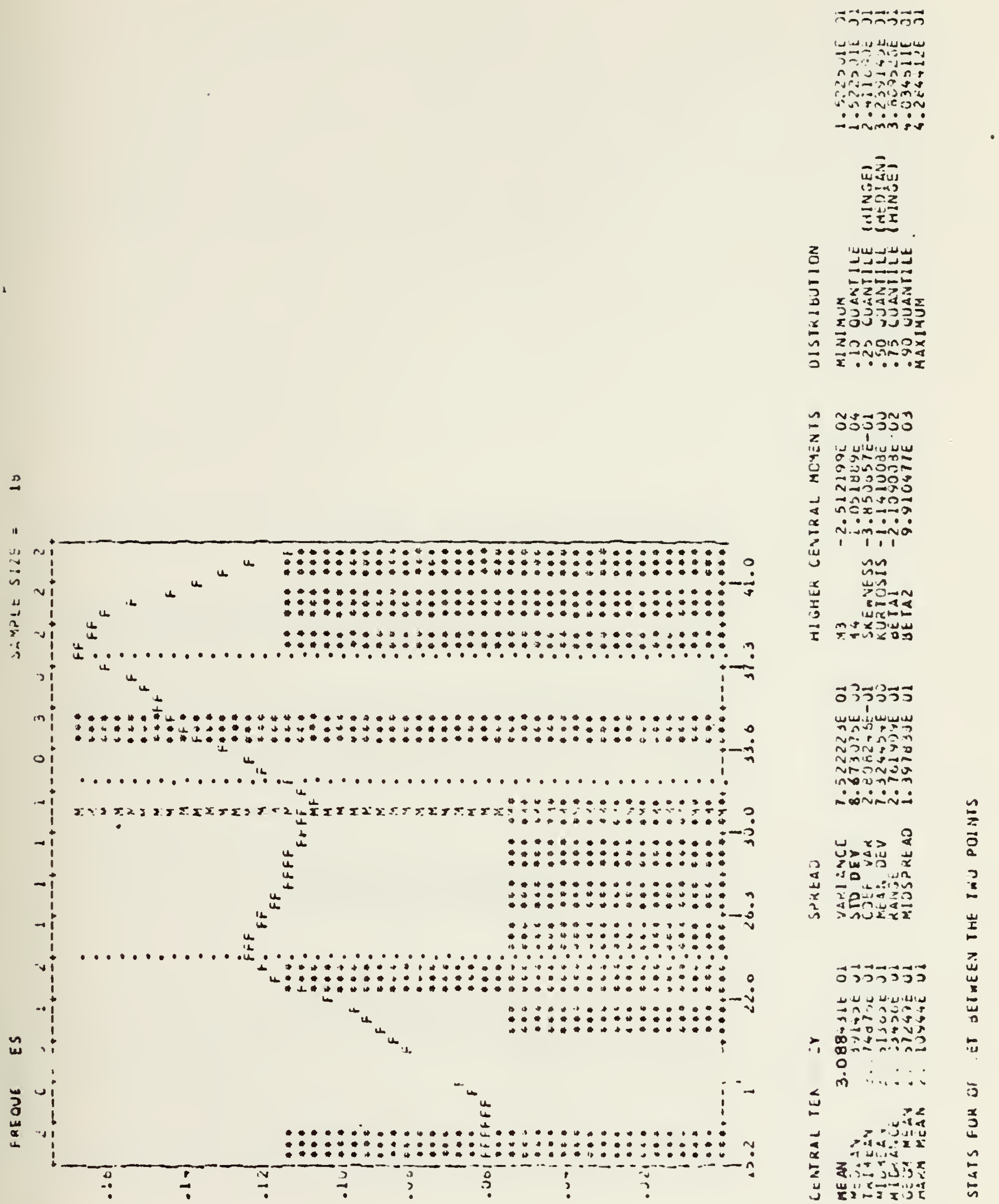


Figure F-2. Original Data and Range Corrections

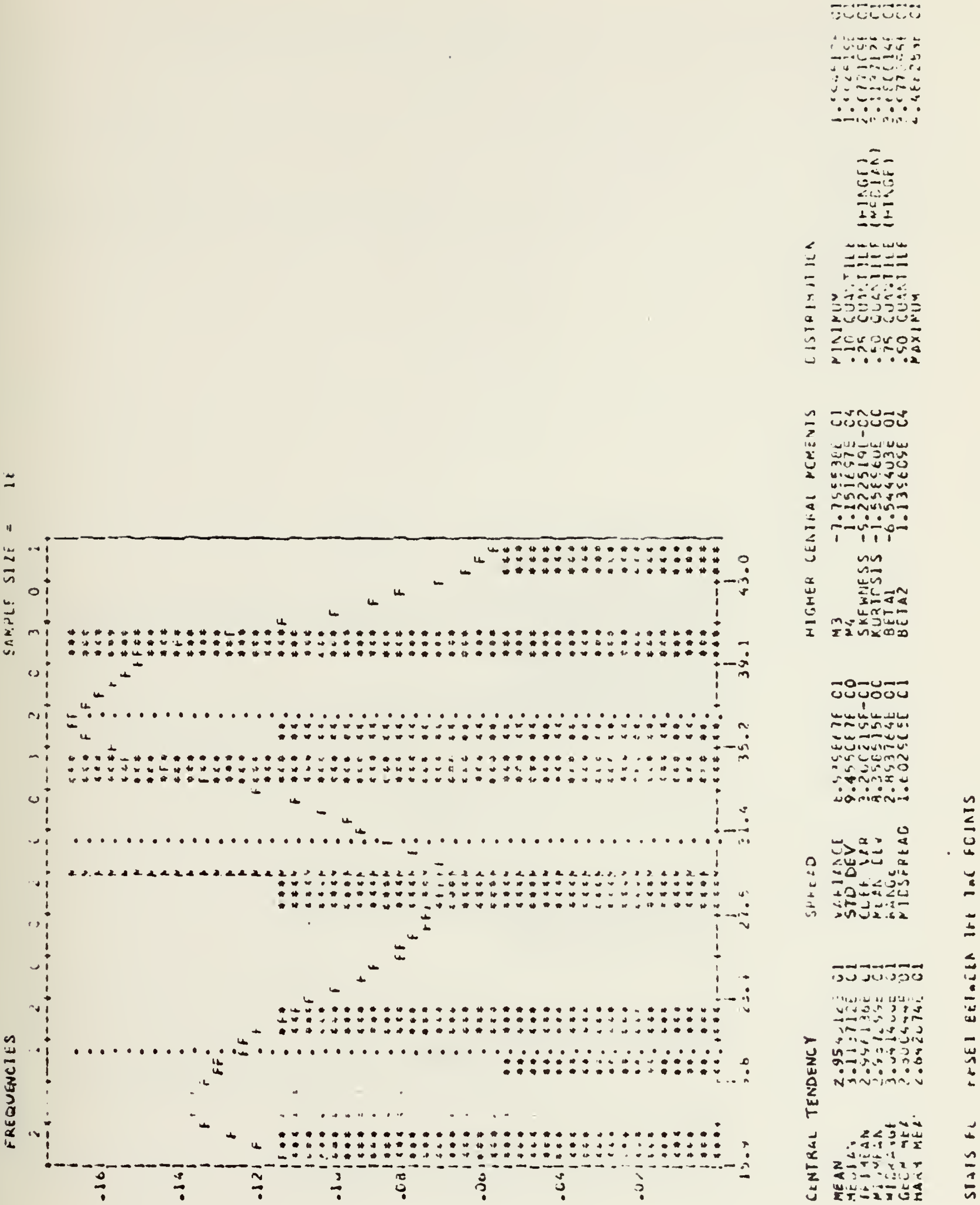


Figure F-3. Original Data and Coordinate Shift

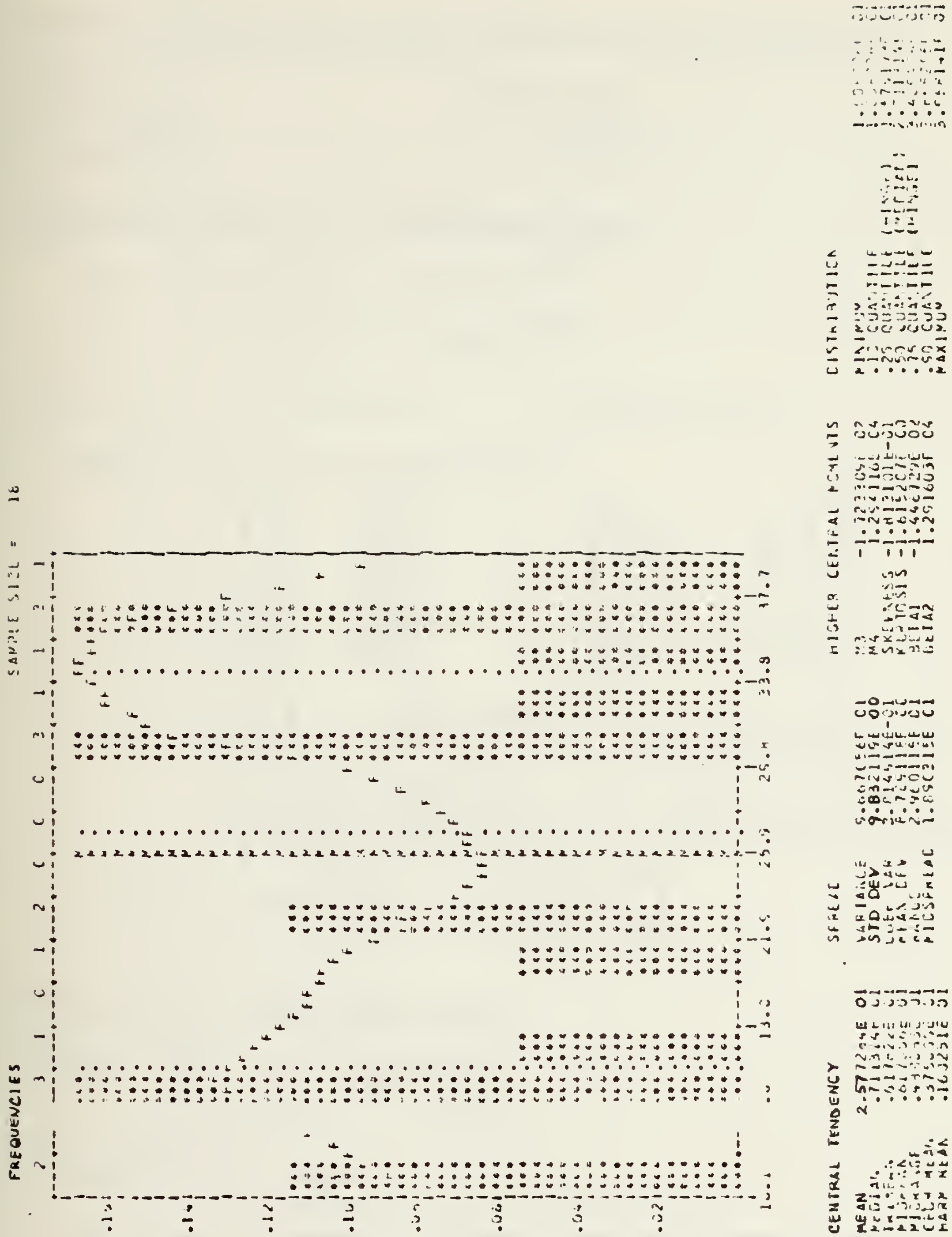


Figure F-4. Original Data and Range Corrections and Coordinate Shift

APPENDIX G
HDOP/GDOP Evaluation

Four points from day 124 found at the north, south, east and west limits of the test area were used to calculate the HDOP for the station configuration.

Station Coordinates (Universal Transverse Mercator (WGS-72))

Monterey Bay 4

x_1 = 603425.2
y_1 = 4053917.2

Luces Point

x_1 = 595794.5
y_1 - 4055042.7

Observation Equation for Range-Range System:

$$S_{10} = F_1 = [(x_o-x_1)^2 + (y_o-y_1)^2]^{1/2}$$

$$S_{20} = F_2 = [(x_o-x_2)^2 + (y_o-y_2)^2]^{1/2}$$

Solve: $Gx + L = v = 0$ for x: (v is the residual)

where G is the observation matrix

$$G = \begin{bmatrix} \frac{\partial F_1}{\partial x_o} & \frac{\partial F_1}{\partial y_o} \\ \frac{\partial F_2}{\partial x_o} & \frac{\partial F_2}{\partial y_o} \end{bmatrix} = \begin{bmatrix} \frac{x_o-x_1}{S_{10}} & \frac{y_o-y_1}{S_{10}} \\ \frac{x_o-x_2}{S_{20}} & \frac{y_o-y_2}{S_{20}} \end{bmatrix}$$

$x = \begin{bmatrix} dx \\ dy \end{bmatrix}$ differences to add to successive position values (either assumed or computed)

$L = \begin{bmatrix} S_{1p}-S_{10} \\ S_{2p}-S_{20} \end{bmatrix}$ observation vector where S_{op} is the observed value and S_{xx} is computed value using an assumed initial position.

$x = G^{-1}L$ $\quad$ new $\begin{bmatrix} x_o \\ y_o \end{bmatrix}$ = old $\begin{bmatrix} x_o \\ y_o \end{bmatrix} + \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix}$

I. North Limit Event Number 21099 .

Ranges: MB4 S_{1p} = 9028 meters
Luces S_{2p} = 8713 meters

First Iteration:
Assume: x_o = -600000
y_o = 4059200

Solve for S_{10} and S_{20}

$$S_{10} = \sqrt{(x_o-x_1)^2 + (y_o-y_1)^2} = \sqrt{(600000-603425.2)^2 + (4059200-4053917.2)^2}$$

= 6296.0 meters

$$S_{20} = \sqrt{(x_o-x_2)^2 + (y_o-y_1)^2} = \sqrt{(600000-595794.5)^2 + (4059200-4055042.7)^2}$$

= 5913.5 meters

$$G = \begin{bmatrix} \frac{600000-603425.2}{6296} & \frac{4059200-4053917.2}{6296} \\ \frac{600000-595794.5}{5913.5} & \frac{4059200-4055042.7}{5913.5} \end{bmatrix} = \begin{bmatrix} -.544 & .839 \\ .711 & .703 \end{bmatrix}$$

$$L = \begin{bmatrix} 9028-6296 \\ 8713-5913 \end{bmatrix} = \begin{bmatrix} 2732 \\ 2800 \end{bmatrix}$$

$$G^{-1} = \frac{-1.021}{(-.544)(.703)-(.839)(.711)} \begin{bmatrix} .703 & -.839 \\ -.711 & -.544 \end{bmatrix} = \begin{bmatrix} -.718 & .857 \\ .726 & .556 \end{bmatrix}$$

$$x = G^{-1}L = \begin{bmatrix} 438.0 \\ 3540.2 \end{bmatrix} = \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix}$$

$$x_o = x_o + \Delta x = 600000 + 438.0 = 600438.0$$

$$y_o = y_o + \Delta y = 4059200 + 3540.2 = 4062740.2$$

Second Iteration:

$S_{10} = 9315.0$

$S_{20} = 8989.6$

$$G = \begin{bmatrix} \frac{-2987.2}{9315} & \frac{8823}{9315} \\ \frac{4643.5}{8989.6} & \frac{7697.5}{8989.6} \end{bmatrix} = \begin{bmatrix} -.321 & .947 \\ .517 & .856 \end{bmatrix}$$

$$G^{-1} = -1.310 \begin{bmatrix} \quad \end{bmatrix} = \begin{bmatrix} -1.122 & 1.241 \\ .677 & .421 \end{bmatrix}$$

$$L = \begin{bmatrix} -287 \\ -276.6 \end{bmatrix}$$

$$x = G^{-1}L = \begin{bmatrix} -21.2 \\ -310.7 \end{bmatrix}$$

$$x_o = 600438.0 + (-21.2) = 600416.8$$

$$y_o = 4062740.0 + (-310.7) = 4062429.3$$

Third Iteration:

$S_{10} = 9028.1$

$S_{20} = 8713.6$

$$G = \begin{bmatrix} \frac{-3008.4}{9028.1} & \frac{8512.1}{9028.1} \\ \frac{4622.3}{8713.6} & \frac{7386.6}{3713.6} \end{bmatrix} = \begin{bmatrix} -.333 & .943 \\ .530 & .848 \end{bmatrix}$$

$$G^{-1} = \begin{bmatrix} -1.084 & -1.206 \\ -.678 & .426 \end{bmatrix}$$

$$L = \begin{bmatrix} -.1 \\ -.6 \end{bmatrix}$$

$$x = G^{-1}L = \begin{bmatrix} .832 \\ .198 \end{bmatrix}$$

$$x_o = 600416.8 + .832 = 600417.632$$

$$y_o = 4062429.3 + .198 = 4062429.498$$

*MRS III position: 600401 $\Delta x = 16.6$
4062345 $\Delta y = 84.5$

NOTE: Range data to either side of this position was lost due to antenna dynamics encountered during a Williamson turn. This is believed to be the cause of the large difference between the two values.

$$\text{Var } x = G \text{ Var } y\ G^T$$

$$= \begin{bmatrix} \sigma_1^2 \\ \\ \sigma_2^2 \end{bmatrix} \qquad \sigma_1 = \sigma_2 = 2 \text{ m}$$

$$\mathrm{Var}\ y = \begin{bmatrix} \sigma_x^2 & o \\ o & \sigma y^2 \end{bmatrix}$$

$$\mathrm{Var}\ y = \mathrm{Var}\ x\ (G^{-1}\ G^{-T})$$

$$= G^2 \begin{bmatrix} -1.08 & -1.2 \\ -.68 & .43 \end{bmatrix} \begin{bmatrix} -1.08 & -.68 \\ -1.2 & .43 \end{bmatrix} = 4 \begin{bmatrix} 2.61 & .22 \\ .22 & .65 \end{bmatrix}$$

$\sigma_x{}^2 = 10.44$ $\qquad\qquad$ $\sigma_x = 3.2$

$\sigma_y 2 = 2.6$ $\qquad\qquad$ $\sigma_y = 1.6$

$$\sigma_y = \sqrt{\alpha_x{}^2 + \sigma_y{}^2} = 3.6$$

σ_h = horizontal uncertainty
= (HDOP)(σ_R) where $_R$ is the rms radial range error.

HDOP = 3.6/2 = 1.8

II. South Limit Event Number 21185.

Ranges: MB4 $\quad S_{1p} = 3371$ m
LUCES $\quad S_{2p} = 5704$ m

Last Iteration:

$$G = \begin{bmatrix} -.630 & .776 \\ .965 & .262 \end{bmatrix}$$

$$G^{-1} = \begin{bmatrix} -.287 & .849 \\ 1.056 & .689 \end{bmatrix}$$

x_o = 601300.6 - .4 = 601300.2
y_o = 4056534.6 - .6 = 4056534.0

MRS III position: 601296 $\qquad$ $\Delta x = 4.2$
4056534 $\qquad$ $\Delta y = 0.0$

$\sigma_x^{2} = 3,2 \qquad \sigma_x = 1.8$

$\sigma_y^{2} = 6.4 \qquad \sigma_y = 2.5$

$$\alpha_h = \sqrt{\sigma_x^{2} + \sigma_y^{2}} = 3.1 = \text{HDOP } G_R$$

HDOP = 3.1/2 = 1.6

III. East Limit Event Number 21310

Ranges: MB4 S_{1p} = 0816 m
LUCES S_{2p} = 9704 m

Last Iteration:

$$G = \begin{bmatrix} .155 & .988 \\ .879 & .476 \end{bmatrix} \qquad G^{-1} = \begin{bmatrix} -.599 & 1.243 \\ 1.106 & -.195 \end{bmatrix}$$

x_o = 604327.6 + .5 = 604328.1
y_o = 4059663.5 - .8 = 4059662.7

MRS III positions: 604328 $\Delta x = 0.1$
4059665 $\Delta y = 3.3$

$\sigma_h = \text{HDOP } \sigma_R = \sqrt{7.6 + 5.2} = 3.6$
HDOP = 3.6/2 = 1.8

IV. West Limit Event Number 21411.

Ranges: MB4 S_{1p} = 7128 m
LUCES S_{2p} = 3691 m

Last Iteration:

$$G = \begin{bmatrix} -.8 & .6 \\ .522 & .853 \end{bmatrix} \qquad G^{-1} = \begin{bmatrix} -.857 & .603 \\ .524 & .804 \end{bmatrix}$$

x_o = 597720.7
y_o = 4058191

MRS III positions: 597720 $\Delta x = 0.7$
4058192 $\Delta y = 0.8$

$$\sigma_n = \text{HDOP } \sigma_R = \sqrt{\sigma_x^{2} + \sigma_y^{2}} = 2.8$$

HDOP = 2.8/2 = 1.4

APPENDIX H : MRS III RANGE HOLE GRAPH

The graph in Figure   shows the approximate locations of the center of range holes for a receiver antenna 10m above the water surface. The width of the hole is not plotted but depends on the distance between the control and reference station, transmitter output power, and receiver sensitivity. The following formula using a flat earth approximation was used to compute the various lines:

$$h_1 = \frac{n\lambda R}{2h_2}$$

where: h_1 = height of reference station in meters

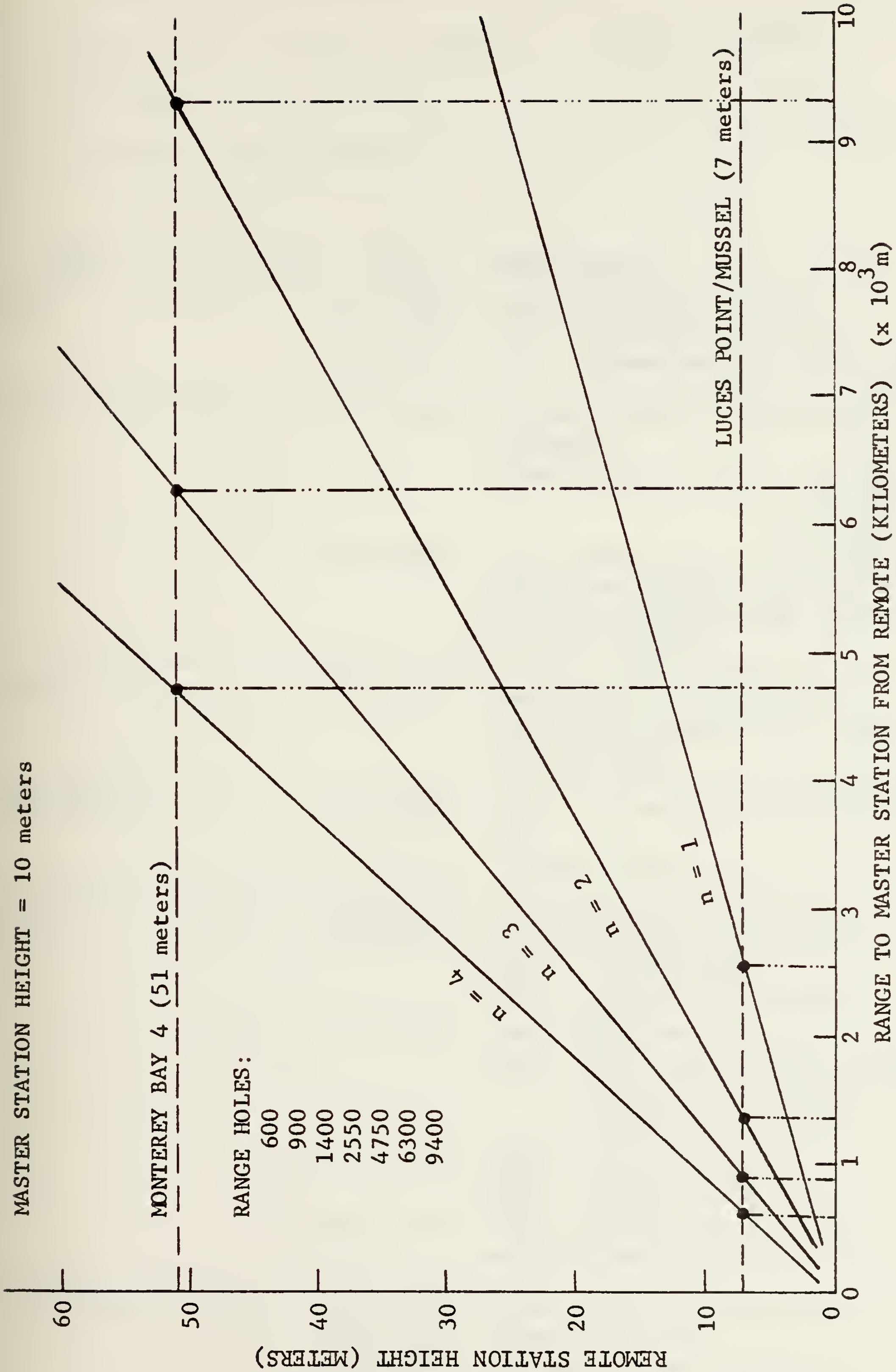
h_2 = height of receiver in meters

λ = wavelength of MRS III system (5.4 cm for f = 5500MHz)

R = range between receiver and reference stations in meters

n = inter order range hole (wavelength multiple)

The heights of the reference stations are indicated on the graph showing the ranges at which different order path lengths have a potential for destructive interference.



MASTER STATION HEIGHT = 10 meters
MONTEREY BAY 4 (51 meters)
RANGE HOLES:
600
900
1400
2550
4750
6300
9400
LUCES POINT/MUSSEL (7 meters)
n = 1
n = 2
n = 3
n = 4
RANGE TO MASTER STATION FROM REMOTE (KILOMETERS) (x 10^3 m)
REMOTE STATION HEIGHT (METERS)
0
10
20
30
40
50
60
1
2
3
4
5
6
7
8
9
10

Figure H-1

APPENDIX I: HISTOGRAMS FOR TRACK LINES: DAYS 121-128

F = Empirical Density Function

$$\bar{F}_n(z) = \frac{1}{nB(n)} \sum_{i=1}^{n} w((x_i - z)/B(n)) \qquad B(n) = \text{Range}/\sqrt{n}$$

m = mean

$$w(z) = \begin{cases} 0 & \text{if } z>1 \\ 1 - z & \text{otherwise} \end{cases}$$

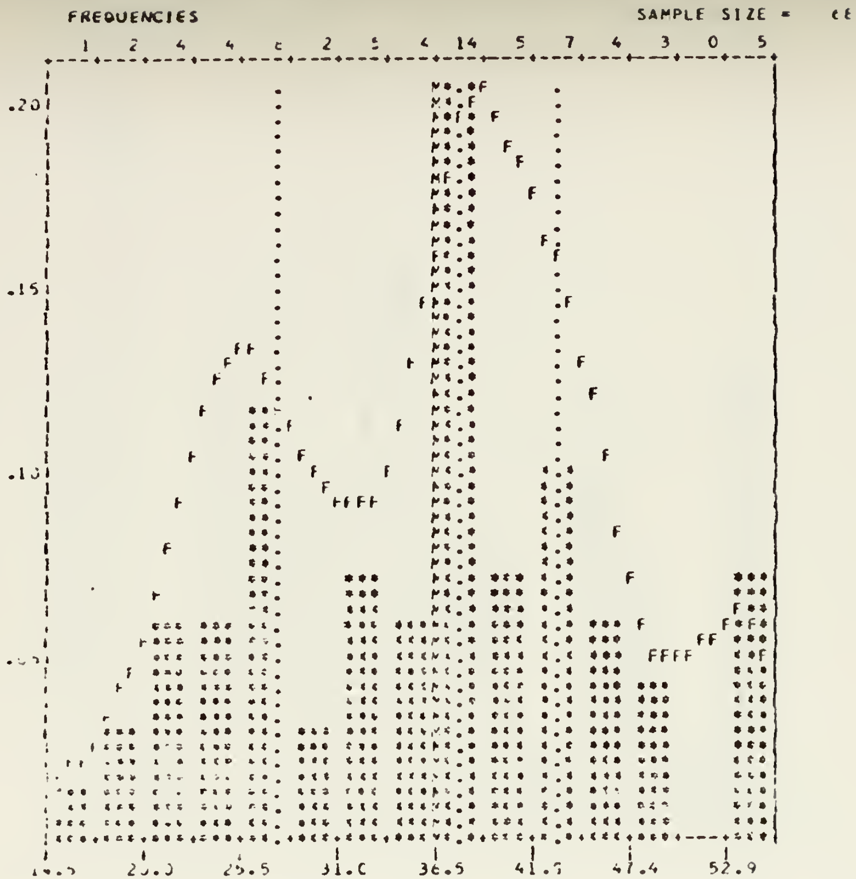
n = number of data points

TEST	DAY	LINE	TIME	OBSERVATIONS
BEACH	121	L2	0811-9822 0839-0844	Four satellites(4,5,6,8) 0830 - update of satellites 4 and 6 is reason for two sets of data
PIER	122	L1	0710-0725	Antenna cable too long; causes multiple peaks Upload of satellites: 4 at 0715 6 at 0715 8 at 0715
		L2	0848-0912	Three satellites at start; 0854 - two satellites; 0904 - one satellite Antenna cable too long; caused loss of satellite signals
ANCHOR	123	L1	0738-0814	Four satellites (4,5,6,8) Satellite 4 updated three times: 0700, 0730, and 0845
HIGH-DYANMIC	124	L1	0600-0647	0626 - dropped one satellite leaving two
		L2	0727-0811	Two satellites
CIRCLE	125	L1	0540-0620	Two satellites until 0551, gained one
		L2	0638-0718	Three satellites pre-update 0640 - 4 satellites 0709 - update of satellites
		L3	0755-0820	Four satellites 0805 - picked up satellite 7; peak at right due to bad satellite (7) in position solution
		L4	0826-0839	Five satellites (4,5,6,7,8) 0830 - lost satellite 4 0838 - update of satellite 7
		L5	0901-0920	Four satellites (4,5,6,7) Large offset due to satellite 7
5-Knot test	126	L1	0558-0615	Three satellites; Pre-update (4,6,8)
		L2	0622-0637	Three satellites
		L3	0652-0708	Four satellites (4,5,6,8)
		L4	0744-0800	Four satellites; variations due to update

		L5	0809-0824	Four satellites
		L6	0844-0902	Three satellites
		L7	0917-0936	Three satellites; weak signal codes
		L8	0950-1007	Three satellites; peak at left due to mislabeling of time on data
9-Knot test	127	L1	0646-0700	Three satellites; pre-update
		L2	0721-0729	Four satellites (4,5,6,8)
		L3	0737-0750	Four satellites
		L4	0800-0815	Four satellites
		L5	0822-0833	0832 - drop to three satellites
		L6	0858-0915	Three satellites
BEACH	128	L1	0631-0805	Four satellites (4,5,6,8); pre/post upload data Uploads complete at 0728
		L2	0735-0805	Four satellites

STATISTICAL BREAKDOWN BY DAY AND BY LINE

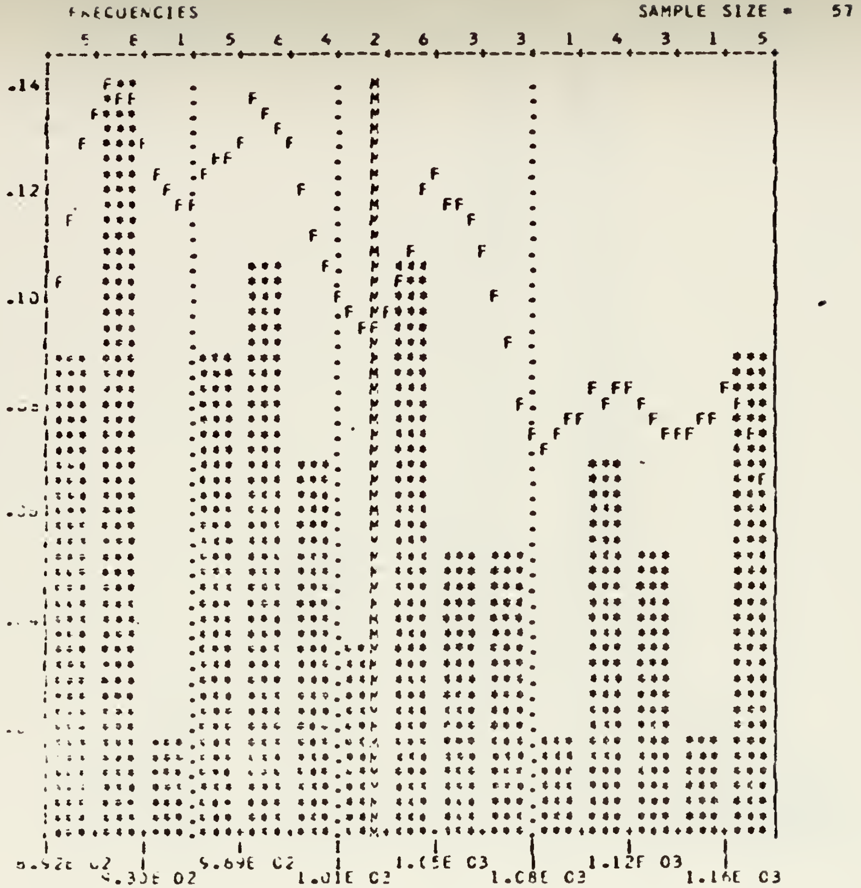
	Mean	Standard Deviation
Beach		
D121L1	--	--
D121L2	36.25	9.82
D128L1	147.28	15.27
D128L2	7.43	3.23
Pier		
D122L1	1018.86	85.81
D122L2	87.04	12.78
Anchor		
D123L1	149.16	95.29
High Dynamic		
D124L1	315.7	19.79
D124L2	1002.16	149.22
Circle		
D125L1	31.10	12.81
D125L2	18.31	9.09
D125L3	297.12	266.20
D125L4	268.09	165.97
D125L5	21088.50	4673.65
D125L6	--	--
9 Knot lines		
D126L1	102.10	4.97
D126L2	116.31	7.16
5 Knot lattice		
D126L3	363.40	100.76
D126L4	43.45	21.19
D126L5	20.52	7.34
D126L6	33.80	9.68
D126L7	42.47	10.16
D126L8	55.37	13.89
D127L1	671.34	133.64
D127L2	187.48	176.78
D127L3	50.58	10.24
D127L4	32.42	12.64
D127L5	30.71	16.20
D127L6	33.25	11.08



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	3.625322E 01	VARIANCE	9.647552E 01	M3	-4.271507E 01	MINIMUM	1.454315E 01
MEDIAN	[illegible]	STD DEV	9.822399E 00	M4	2.136559E 04	.10 QUANTILE	[illegible]
TRIMEAN	[illegible]	COEF VAR	2.709386E-01	SKEWNESS	[illegible]	.25 QUANTILE (HINGE)	[illegible]
MIDMEAN	[illegible]	MEAN DEV	7.900555E 00	KURTOSIS	[illegible]	.50 QUANTILE (MEDIAN)	[illegible]
MIDRANGE	[illegible]	RANGE	[illegible]	BETA1	[illegible]	.75 QUANTILE (HINGE)	[illegible]
GEOM MEAN	[illegible]	MIDSPREAD	1.502476E 01	BETA2	2.0916205 04	.90 QUANTILE	[illegible]
HARM MEAN	[illegible]					MAXIMUM	[illegible]

STATS FOR OFFSET BETWEEN THE TWO POINTS

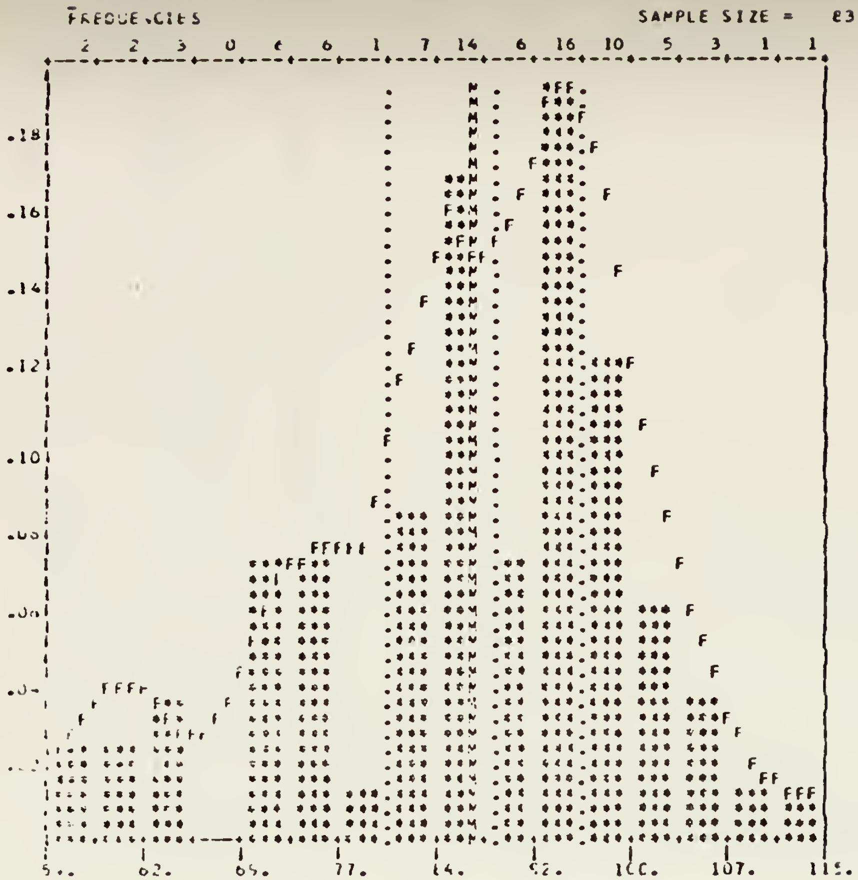
Day 121 Line 2



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	1.018665E 03	VARIANCE	7.362625E 03	M3	1.744097E 05	MINIMUM	8.518130E 02
MEDIAN	1.003570E 03	STD DEV	8.580574E 01	M4	1.010940E 08	.10 QUANTILE	9.058650E 02
TRIMEAN	1.005642E 03	COEF VAR	8.421701E-02	SKEWNESS	2.760715E-01	.25 QUANTILE (HINGE)	9.467561E 02
MIDMEAN	1.012037E 03	MEAN DEV	7.302205E 01	KURTOSIS	-1.135080E 00	.50 QUANTILE (MEDIAN)	1.003570E 03
MIDRANGE	1.015623E 03	RANGE	2.876191E 02	BETA1	1.653377E 05	.75 QUANTILE (HINGE)	1.095433E 03
GEOM MEAN	1.015351E 03	MIDSPREAD	1.386370E 02	BETA2	9.955552E 07	.90 QUANTILE	1.140623E 03
HARM MEAN	1.011682E 03					MAXIMUM	1.179432E 03

STATS FOR OFFSET BETWEEN THE TWO POINTS

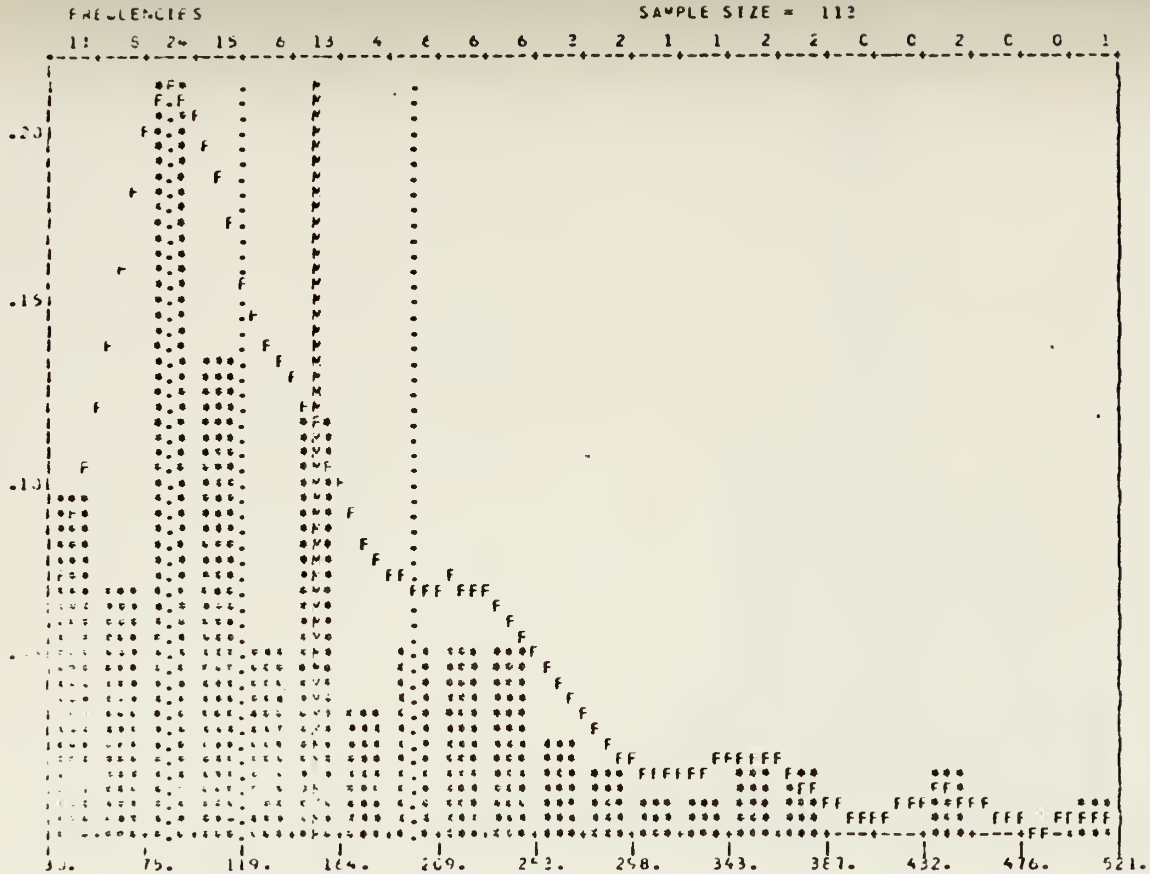
Day 122 Line 1



Day 122 Line 2

CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	8.703732E 01	VARIANCE	1.634293E 02	M3	-1.298502E 03	MINIMUM	5.402267E 01
MEDIAN	8.952133E 01	STD DEV	1.278295E 01	M4	8.056600E 04	.10 QUANTILE	6.933847E 01
TRIMEAN	8.893468E 01	COEF VAR	1.468789E-01	SKEWNESS	-6.215094E-01	.25 QUANTILE (HINGE)	8.085910E 01
MIDMEAN	[illegible]	MEAN DEV	1.001099E 01	KURTOSIS	3.135591E-02	.50 QUANTILE (MEDIAN)	8.952133E 01
MIDRANGE	[illegible]	RANGE	6.093745E 01	BETA1	-1.251946E 03	.75 QUANTILE (HINGE)	9.583413E 01
[illegible] MEAN	[illegible]	MIDSPREAD	1.497503E 01	BETA2	7.896025E 04	.90 QUANTILE	1.008525E 02
[illegible] MEAN	[illegible]					MAXIMUM	1.149651E 02

STATS FOR OFFSET BETWEEN THE TWO POINTS



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	1.491063E 02	VARIANCE	9.080258E 03	M3	1.252834E 06	MINIMUM	3.026636E 01
MEDIAN	1.161354E 02	STD DEV	9.529025E 01	M4	4.266557E 08	.10 QUANTILE	4.557643E 01
TRIMEAN	1.262625E 02	COEF VAR	6.388306E-01	SKEWNESS	1.447926E 00	.25 QUANTILE (HINGE)	6.270439E 01
MIDMEAN	1.257766E 02	MEAN DEV	6.963406E 01	KURTOSIS	2.175016E 00	.50 QUANTILE (MEDIAN)	1.161348E 02
MIDRANGE	2.756057E 02	RANGE	4.906775E 02	BETA1	1.219770E 06	.75 QUANTILE (HINGE)	1.944774E 02
GEOM MEAN	1.246300E 02	MIDSPREAD	1.117730E 02	BETA2	4.159027E 08	.90 QUANTILE	2.674321E 02
HARM MEAN	1.026349E 02					MAXIMUM	5.209446E 02

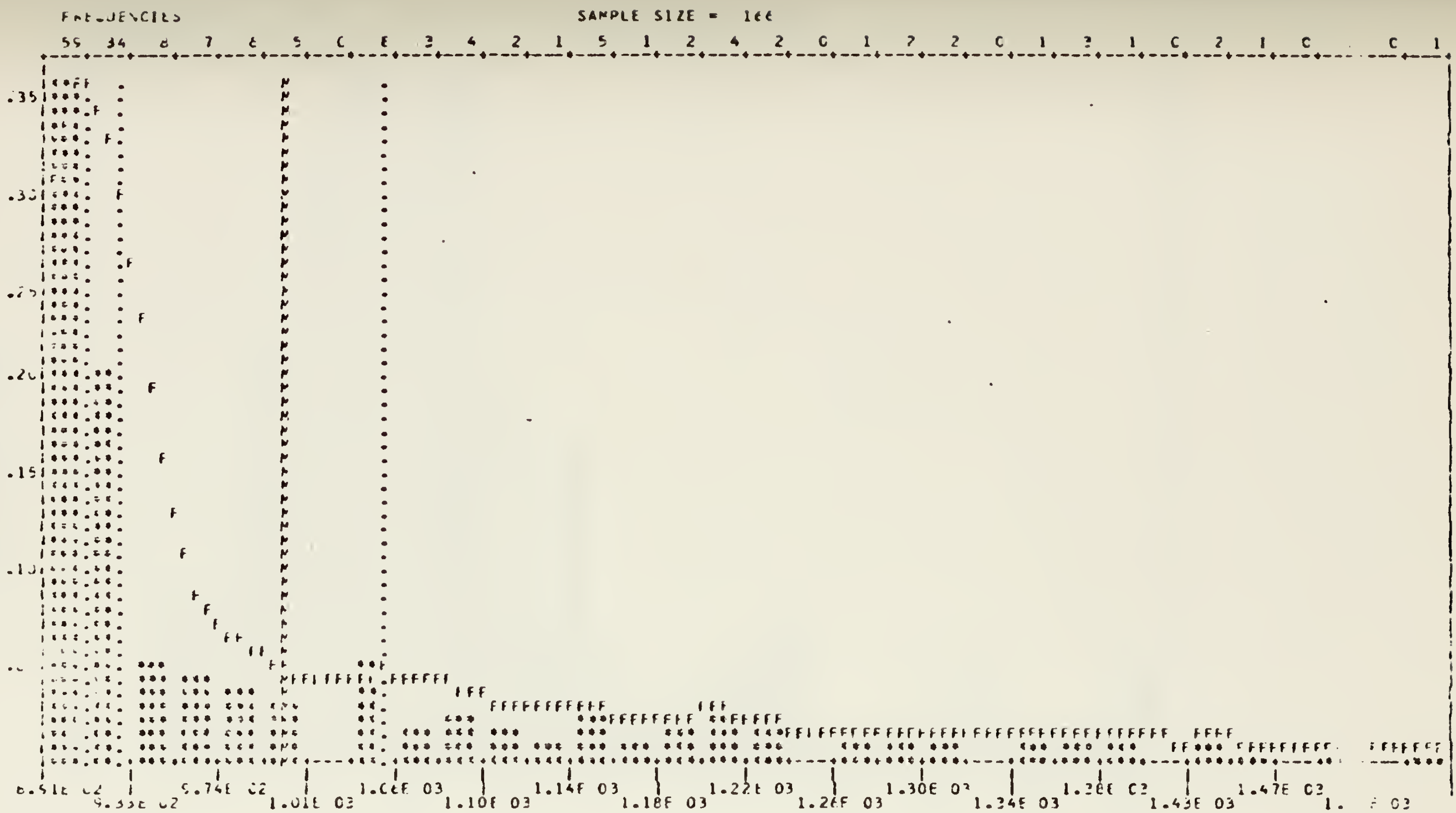
STATS FOR OFFSET BETWEEN THE TWO POINTS

Day 123 Line 1

CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	3.157000E 02	VARIANCE	3.914600E 02	M3	2.070735E 03	MINIMUM	2.165031E 02
MEDIAN	3.135779E 02	STD DEV	1.978535E 01	M4	1.376253E 06	.10 QUANTILE	2.964922E 02
TRIMEAN	3.146515E 02	COEF VAR	6.267136E-02	SKEWNESS	2.673580E-01	.25 QUANTILE (HINGE)	3.047615E 02
MIDMEAN	3.143433E 02	MEAN DEV	1.355673E 01	KURTOSIS	5.960576E 00	.50 QUANTILE (MEDIAN)	3.135779E 02
MIDRANGE	3.073654E 02	RANGE	1.617600E 02	BETA1	2.034549E 03	.75 QUANTILE (HINGE)	3.266705E 02
GEOM MEAN	3.150753E 02	MIDSPREAD	2.188540E 01	BETA2	1.349391E 06	.90 QUANTILE	3.340635E 02
HARM MEAN	3.144451E 02					MAXIMUM	3.526698E 02

STATS FOR OFFSET BETWEEN THE TWO POINTS

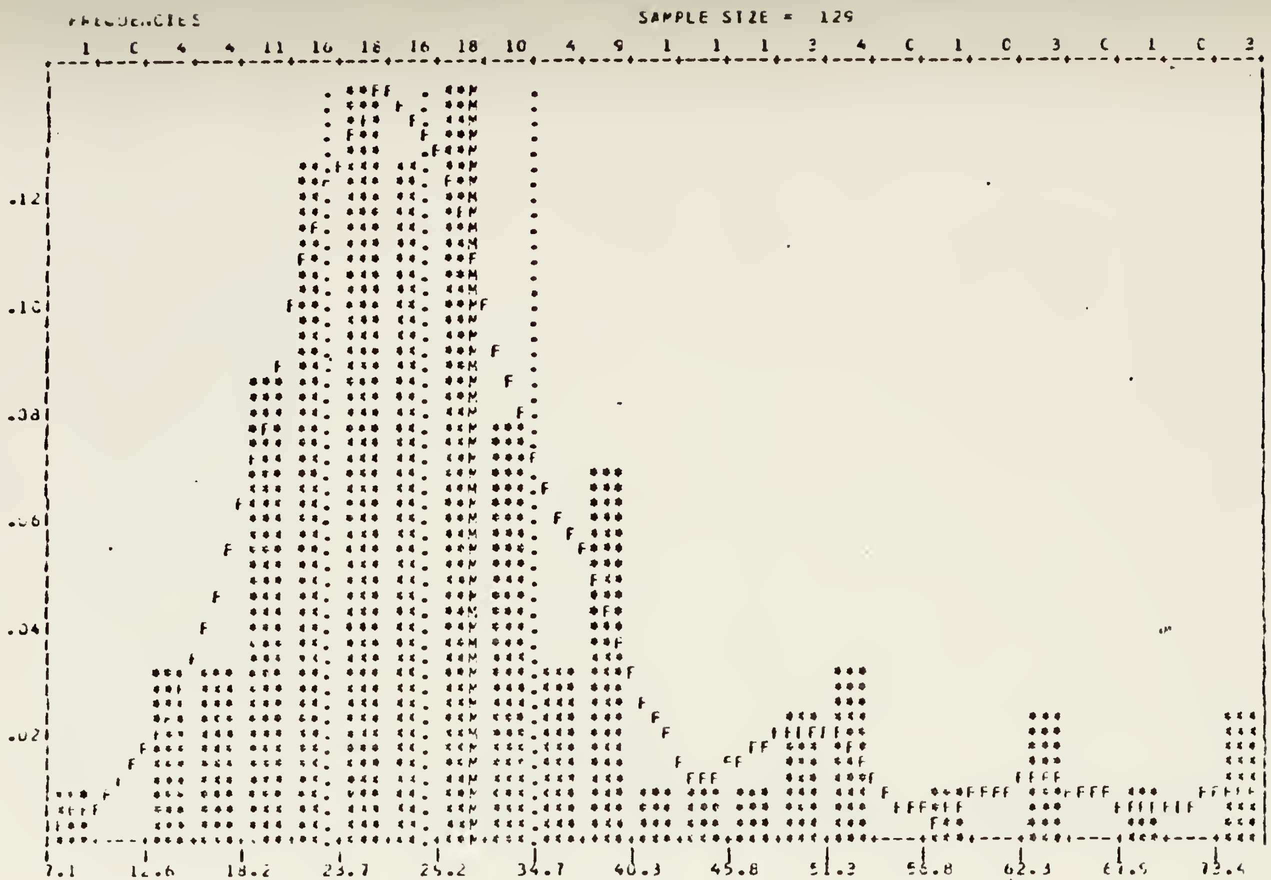
Day 124 Line 1



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	1.002161E 03	VARIANCE	2.226718E 04	M3	5.871558E 06	MINIMUM	8.514407E 02
MEDIAN	9.232976E 02	STD DEV	1.492215E 02	M4	2.626057E 05	.10 QUANTILE	8.955384E 02
TRIMEAN	9.506408E 02	COEF VAR	1.489002E-01	SKEWNESS	1.767077E 00	.25 QUANTILE (HINGE)	9.064441E 02
MIDMEAN	9.421687E 02	MEAN DEV	5.455473E 01	KURTOSIS	2.296316E 00	.50 QUANTILE (MEDIAN)	9.232976E 02
MIDRANGE	1.220064E 03	RANGE	6.572476E 02	BETA1	5.765875E 06	.75 QUANTILE (HINGE)	1.050325E 03
GEOM MEAN	[illegible] 02	MIDSPREAD	1.438806E 02	BETA2	2.580540E 09	.90 QUANTILE	1.216667E 03
HARM MEAN	[illegible] 02					MAXIMUM	1.548688E 03

STATS FOR OFFSET BETWEEN THE TWO POINTS

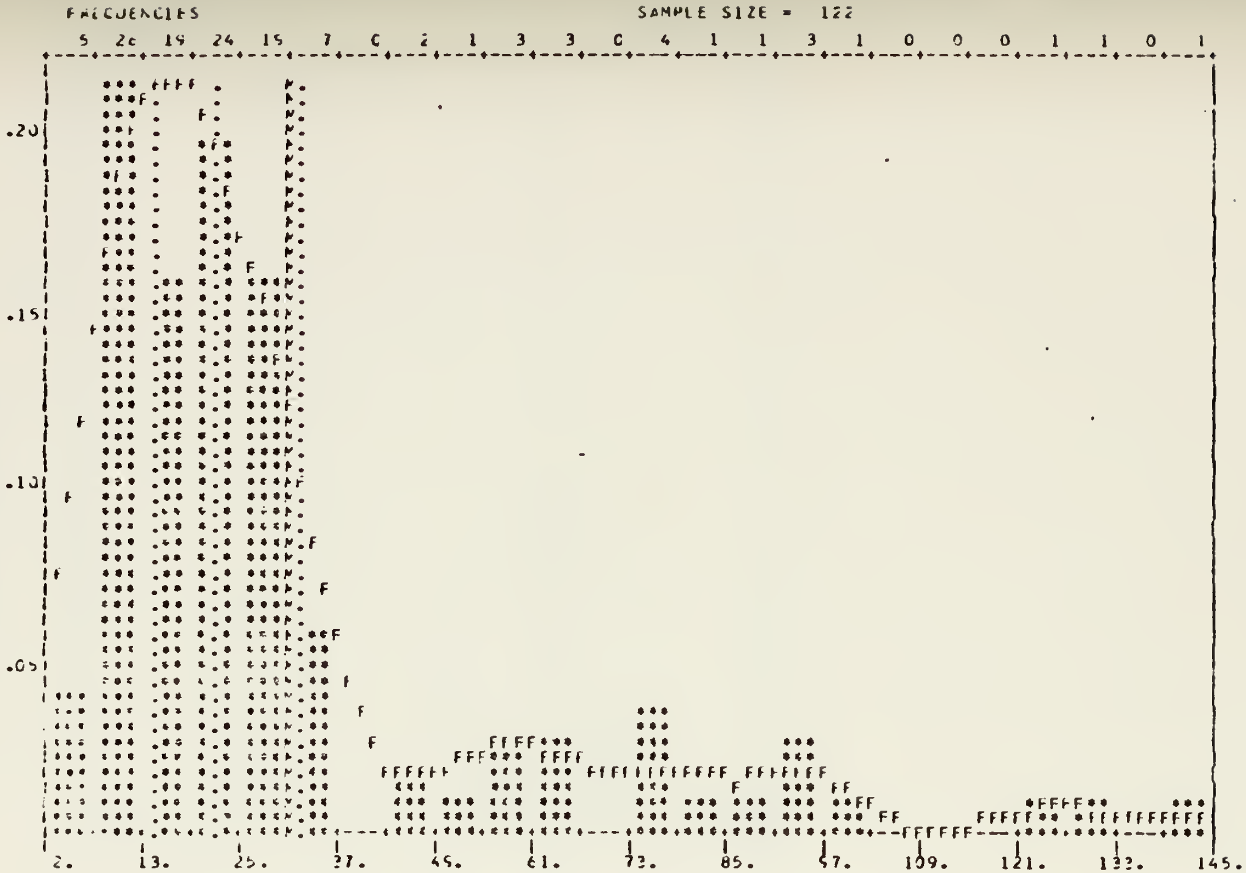
Day 124 Line 2



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	3.1055066E 01	VARIANCE	1.6398666E 02	M3	3.3066C3E 03	MINIMUM	7.1162C9E 00
MEDIAN	2.6101726E 01	STD DEV	1.2805738E 01	M4	1.5340346E 05	.10 QUANTILE	1.5077106E 01
TRIMEAN	2.6376361E 01	COEF VAR	4.1182[illegible]E-01	SKEWNESS	1.5795406E 00	.25 QUANTILE (HINGE)	2.2[illegible]E 01
MIDMEAN	2.8345599E 01	MEAN DEV	8.6515308E 00	KURTOSIS	2.7044946E 00	.50 QUANTILE (MEDIAN)	2.6101725E 01
[illegible]	4.1632771E 01	RANGE	6.9029146E 01	BETA1	3.2320586E 03	.75 QUANTILE (HINGE)	3.4359011E 01
GEOM MEAN	2.5926306E 01	MIDSPREAD	1.1420166E 01	BETA2	1.4566335E 05	.90 QUANTILE	4.9214337E 01
HARM MEAN	2.0555206E 01					MAXIMUM	7.6147356E 01

STATS FOR OFFSET BETWEEN THE TWO POINTS

Day 125 Line 1

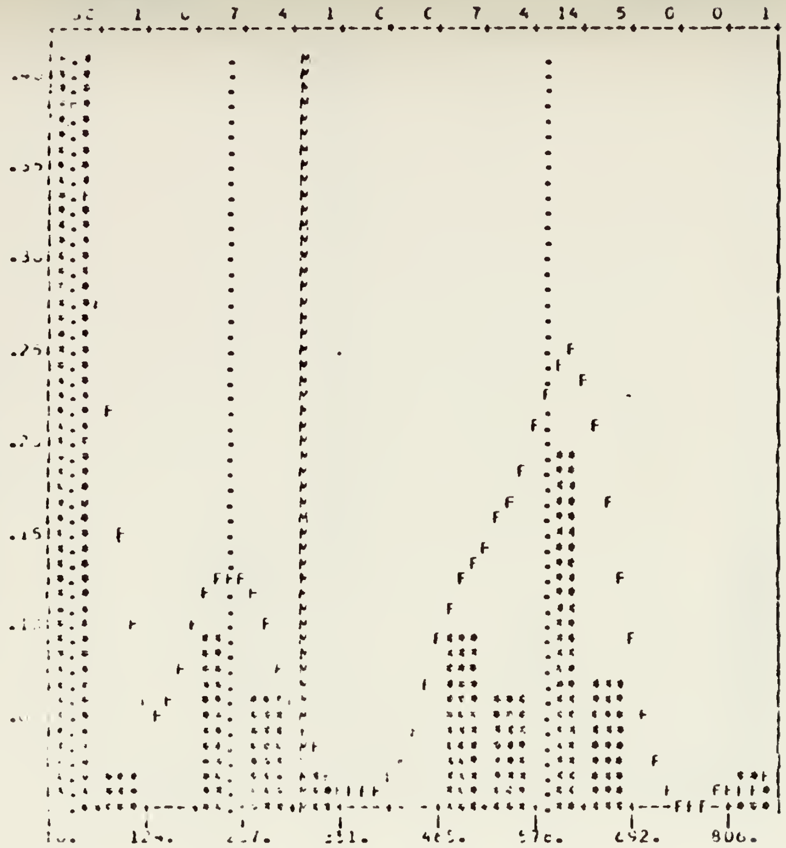


CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	3.005659E 01	VARIANCE	7.359668E 02	M3	4.177148E 04	MINIMUM	1.529220E 00
MEDIAN	2.149540E 01	STD DEV	2.712671E 01	M4	3.540101E 06	.10 QUANTILE	8.967055E 00
TRIMEAN	2.193663E 01	COEF VAR	9.025275E-01	SKEWNESS	2.052149E 00	.25 QUANTILE (HINGE)	1.340021E 01
MIDMEAN	2.177179E 01	MEAN DEV	1.664999E 01	KURTOSIS	4.274295E 00	.50 QUANTILE (MEDIAN)	2.149540E 01
MIDRANGE	7.320528E 01	RANGE	1.433521E 02	BETA1	4.074553E 04	.75 QUANTILE (HINGE)	3.134753E 01
GEOM MEAN	2.215361E 01	MIDSPREAD	1.794731E 01	BETA2	3.837237E 06	.90 QUANTILE	6.906476E 01
HARM MEAN	1.633003E 01					MAXIMUM	1.446813E 02

STATS FOR OFFSET BETWEEN THE TAC POINTS

Day 125 Line 2

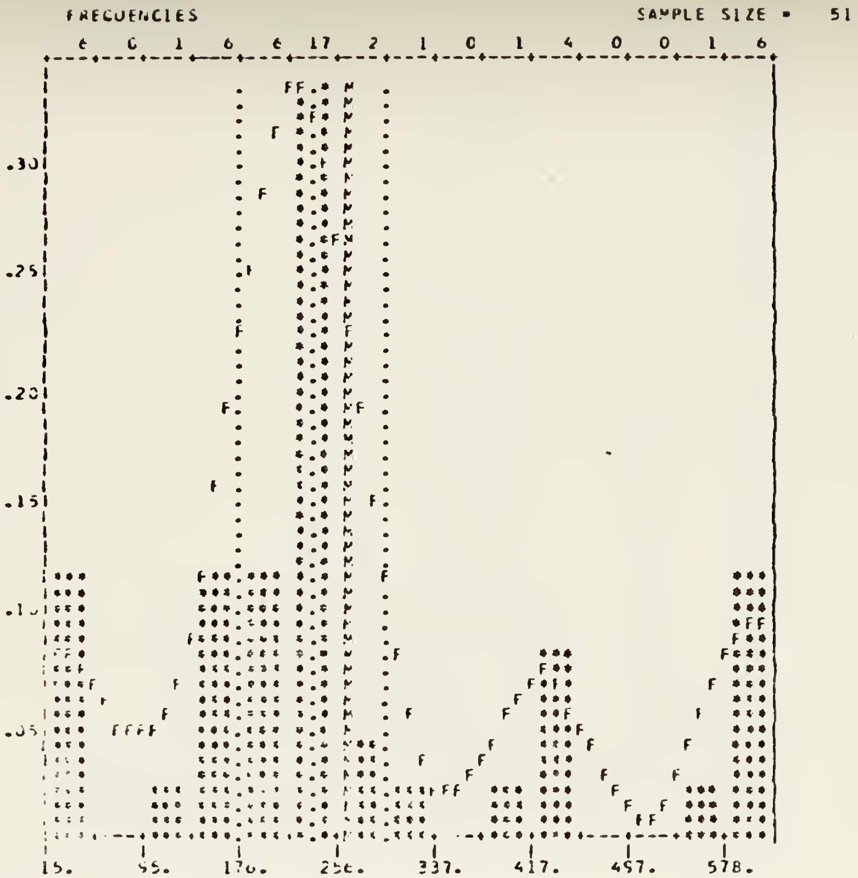
FREQUENCIES SAMPLE SIZE = 74



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	2.971182E 02	VARIANCE	7.086500E 04	M3	4.966625E 06	MINIMUM	5.9073[illegible]E 00
MEDIAN	2.223754E 02	STD DEV	2.662064E 02	M4	6.910206E 09	.10 QUANTILE	1.775214E 01
TRIMEAN	2.673606E 02	COEF VAR	8.959561E-01	SKEWNESS	2.632836E-01	.25 QUANTILE (HINGE)	2.658154E 01
MIDMEAN	2.601733E 02	MEAN DEV	2.404265E 02	KURTOSIS	-1.623574E 00	.50 QUANTILE (MEDIAN)	2.223754E 02
MIDRANGE	4.367565E 02	RANGE	8.527026E 02	BETA1	4.769010E 06	.75 QUANTILE (HINGE)	5.561504E 02
GEOM MEAN	1.354[illegible]E 02	MIDSPREAD	5.716084E 02	BETA2	6.935564E 09	.90 QUANTILE	[illegible] E 02
HARM MEAN	5.007425E 01					MAXIMUM	8.[illegible]E 02

STATS FOR OFFSET BETWEEN THE TWO POINTS

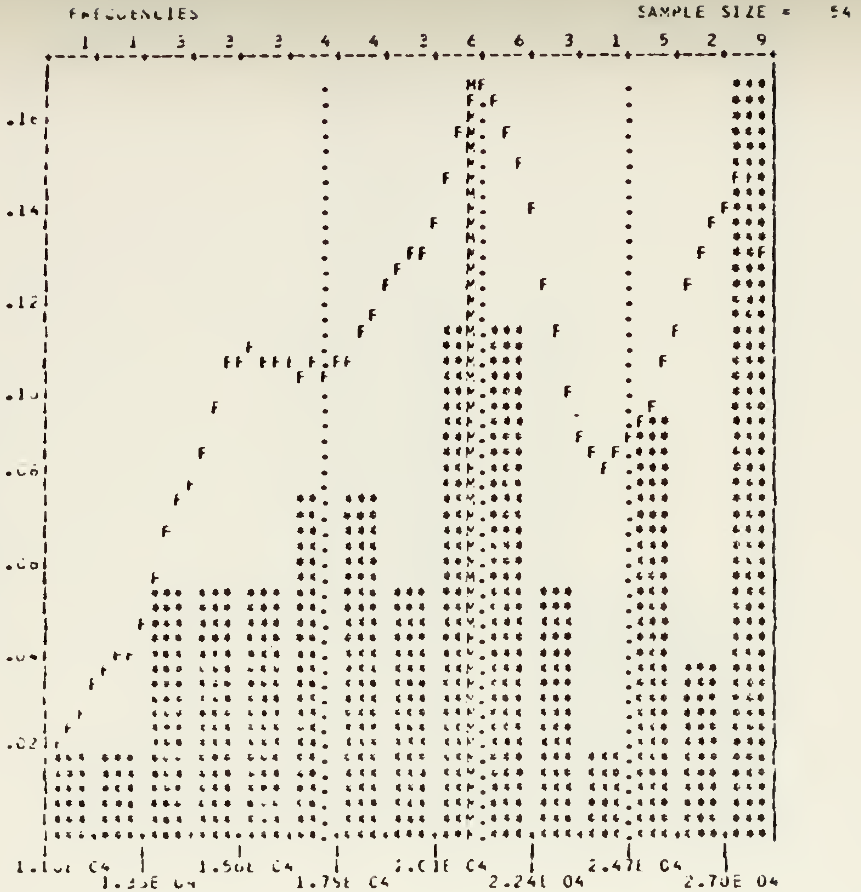
Day 125 Line 3



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION		
MEAN	2.680947E 02	VARIANCE	2.754514E 04	M3	3.724551E 06	MINIMUM		1.483340E 01
MEDIAN	2.300152E 02	STD DEV	1.659673E 02	M4	2.251268E 09	.10 QUANTILE		3.282919E 01
TRIMEAN	2.323215E 02	COEF VAR	6.190671E-01	SKEWNESS	8.147249E-01	.25 QUANTILE	(HINGE)	1.695435E 02
MIDMEAN	2.315806E 02	MEAN DEV	1.137085E 02	KURTOSIS	-3.286743E-02	.50 QUANTILE	(MEDIAN)	2.300152E 02
MIDRANGE	3.154600E 02	RANGE	6.032534E 02	BETA1	3.508362E 06	.75 QUANTILE	(HINGE)	2.557043E 02
GEOM MEAN	2.054073E 02	MIDSPREAD	1.301609E 02	BETA2	2.161372E 09	.90 QUANTILE		5.774768E 02
HARM MEAN	1.186558E 02					MAXIMUM		6.160869E 02

STATS FOR OFFSET BETWEEN THE TWO POINTS

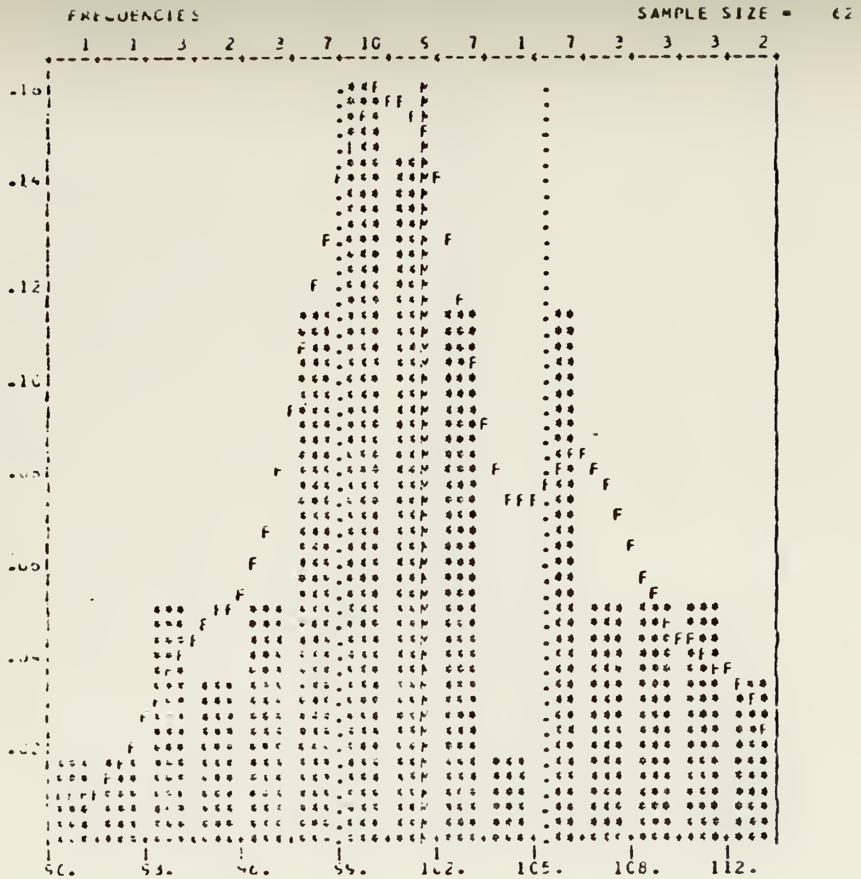
Day 125 Line 4



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	2.108850E 04	VARIANCE	2.184294E 07	M3	-1.567141E 10	MINIMUM	1.103196E 04
MEDIAN	2.121653E 04	STD DEV	4.673645E 03	M4	9.566277E 14	.10 QUANTILE	1.424573E 04
TRIMEAN	2.121051E 04	COEF VAR	2.216205E-01	SKEWNESS	-1.554708E-01	.25 QUANTILE (HINGE)	1.735563E 04
MIDMEAN	2.116121E 04	MEAN DEV	3.842540E 03	KURTOSIS	-5.545703E-01	.50 QUANTILE (MEDIAN)	2.121653E 04
MIDRANGE	1.957676E 04	RANGE	1.708959E 04	BETA1	-1.500506E 10	.75 QUANTILE (HINGE)	2.501055E 04
GEOM MEAN	2.054553E 04	MIDSPREAD	7.611320E 03	BETA2	5.373076E 14	.90 QUANTILE	2.735265E 04
HARM MEAN	1.997082E 04					MAXIMUM	2.812155E 04

STATS FOR OFFSET BETWEEN THE TWO POINTS

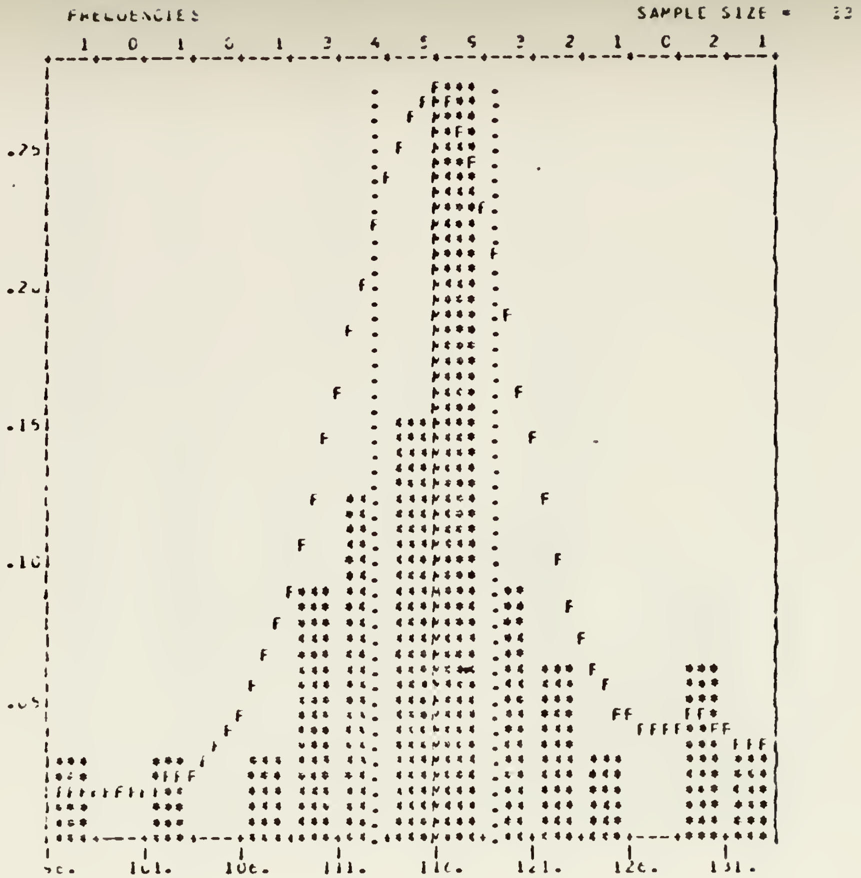
Day 125 Line 5



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	1.021015E 02	VARIANCE	2.471EECE 01	M3	1.682577E 01	MINIMUM	8.986839E 01
MEDIAN	1.017472E 02	STD DEV	4.97180CE 00	M4	1.673664E 03	.10 QUANTILE	9.545573E 01
TRIMEAN	1.021030E 02	COEF VAR	4.86947CE-02	SKEWNESS	1.370236E-01	.25 QUANTILE (HINGE)	9.902465E 01
MIDMEAN	1.017460E 02	MEAN DEV	3.E79924E 00	KURTOSIS	-2.6CE633E-01	.50 QUANTILE (MEDIAN)	1.017472E 02
MIDRANGE	1.015073E 02	RANGE	2.32777E2E 01	BETA1	1.663371E 01	.75 QUANTILE (HINGE)	1.05FE(7E 02
GEOM MEAN	1.019625E 02	MIDSPREAD	6.852CC5E 00	BETA2	1.623356E 03	.90 QUANTILE	1.0F9C6/E 02
HARM MEAN	1.018038E 02					MAXIMUM	1.131402E 02

STATS FOR OFFSET BETWEEN THE TWO POINTS

Day 126 Line 1

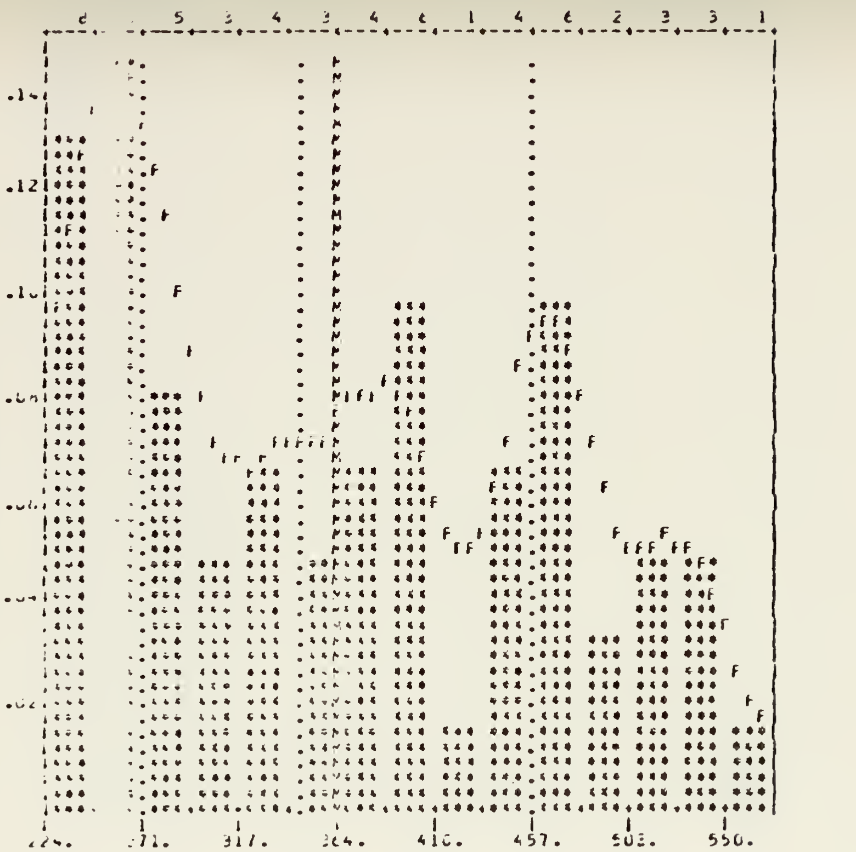


Day 126 Line 2

CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	1.163074E 02	VARIANCE	5.131020E 01	M3	-2.776017E 01	MINIMUM	9.646156E 01
MEDIAN	1.164505E 02	STD DEV	7.163114E 00	M4	1.175799E 04	.10 QUANTILE	1.079036E 02
TRIMEAN	1.162747E 02	COEF VAR	6.156774E-02	SKEWNESS	-7.558393E-02	.25 QUANTILE (HINGE)	1.129236E 02
MIDMEAN	1.161867E 02	MEAN DEV	4.890787E 00	KURTOSIS	1.466073E 00	.50 QUANTILE (MEDIAN)	1.164505E 02
MIDRANGE	1.150351E 02	RANGE	3.715517E 01	BETA1	-2.530573E 01	.75 QUANTILE (HINGE)	1.192735E 02
GEOM MEAN	1.160514E 02	MIDSPREAD	6.349859E 00	BETA2	1.079085E 04	.90 QUANTILE	1.222556E 02
HARM MEAN	1.158722E 02					MAXIMUM	1.336167E 02

STATS FOR OFFSET BETWEEN THE TWO POINTS

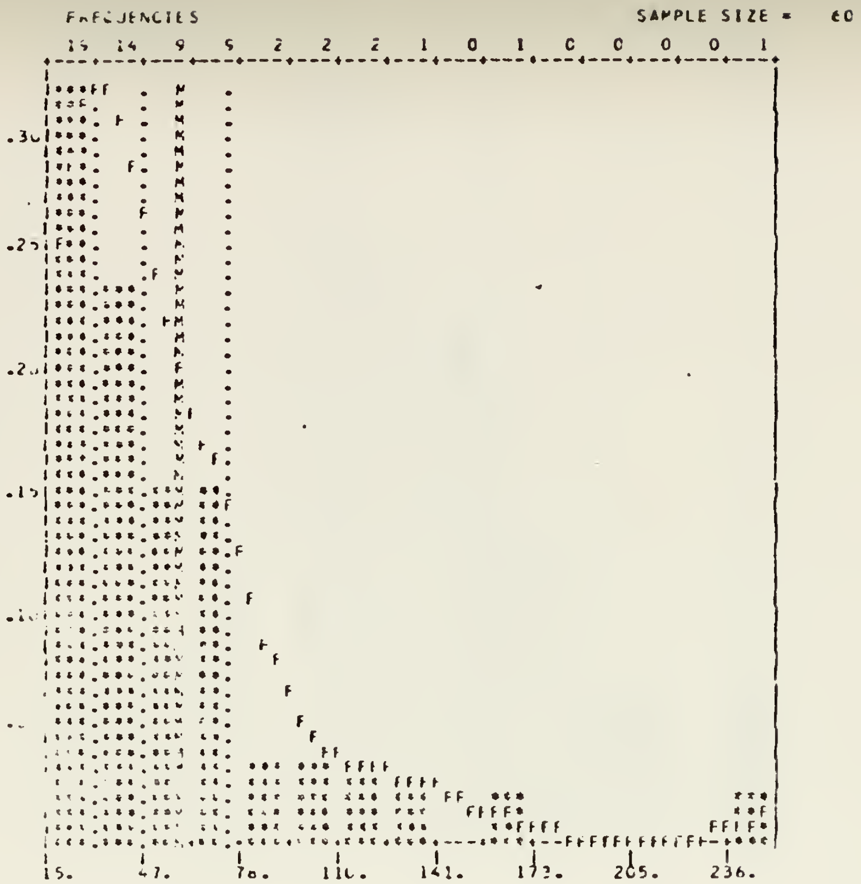
FREQUENCIES SAMPLE SIZE = 62



CENTRAL	DENSITY	SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION		
MEAN	3.634041E 02	VARIANCE	1.015271E 04	M3	3.244821E 05	MINIMUM		2.243[illegible] 02
MEDIAN	3.470079E 02	STD DEV	1.007607E 02	M4	1.626981E 08	.10 QUANTILE		2.406277E 02
TRIMEAN	3.5[illegible] 02	COEF VAR	2.772690E-01	SKEWNESS	3.171604E-01	.25 QUANTILE	(HINGE)	2.6[illegible] 02
MIDMEAN	3.535165E 02	MEAN DEV	8.722200E 01	KURTOSIS	-1.227569E 00	.50 QUANTILE	(MEDIAN)	3.470[illegible] 02
MID-RANGE	3.[illegible] 02	RANGE	3.485225E 02	BETA1	3.[illegible] 05	.75 QUANTILE	(HINGE)	4.5[illegible] 02
GEOM MEAN	3.4[illegible] 02	MIDSPREAD	1.914655E 02	BETA2	1.606446E 08	.90 QUANTILE		4.85[illegible] 02
HARM MEAN	3.363308E 02					MAXIMUM		5.729207E 02

STATS FOR OFFSET BETWEEN THE TWO POINTS

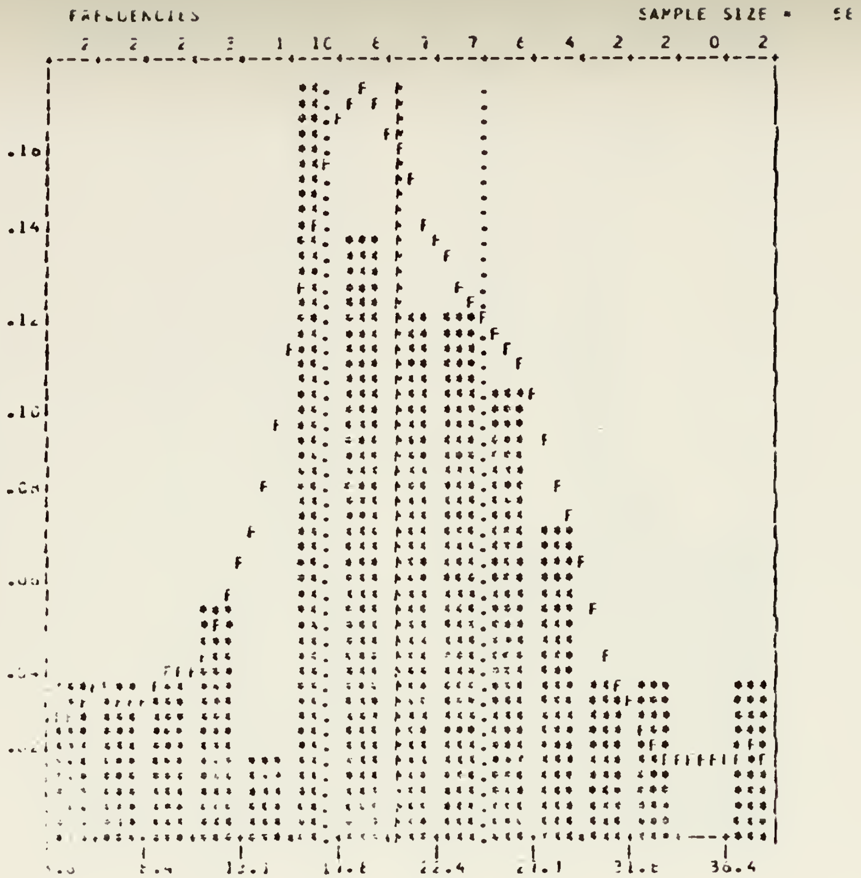
Day 126 Line 3



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	5.416830E 01	VARIANCE	1.694538E 03	M3	1.733565E 05	MINIMUM	1.499644E 01
MEDIAN	4.218292E 01	STD DEV	4.116476E 01	M4	3.177874E 07	.10 QUANTILE	2.129[illegible]E 01
TRIMEAN	4.525494E 01	COEF VAR	7.599419E-01	SKEWNESS	2.465212E 00	.25 QUANTILE (HINGE)	2.623433E 01
MIDMEAN	4.395100E 01	MEAN DEV	2.668457E 01	KURTOSIS	8.067100E 00	.50 QUANTILE (MEDIAN)	4.218292E 01
MIDRANGE	1.334618E 02	RANGE	2.369308E 02	BETA1	1.647850E 05	.75 QUANTILE (HINGE)	7.041[illegible]55E 01
GEOM MEAN	4.407420E 01	MIDSPREAD	4.418532E 01	BETA2	2.994096E 07	.90 QUANTILE	9.766066E 01
HARM MEAN	3.715169E 01					MAXIMUM	2.519273E 02

STATS FOR OFFSET BETWEEN THE TWO POINTS

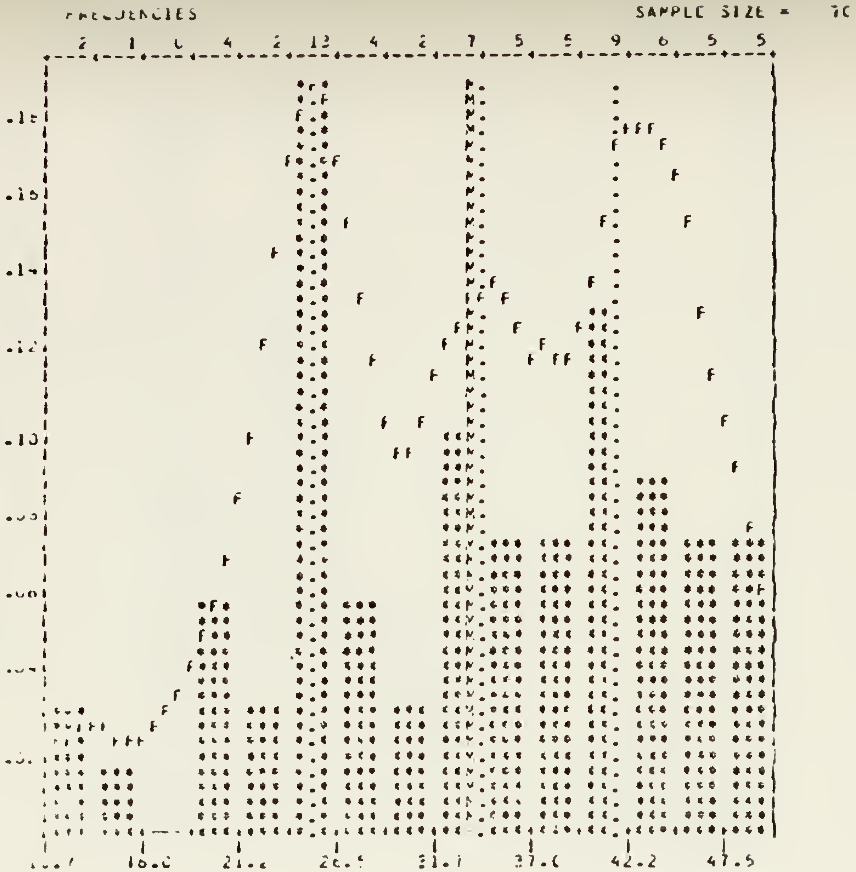
Day 126 Line 4



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	2.052194E 01	VARIANCE	5.392258E 01	M3	1.753724E 01	MINIMUM	3.778770E 00
MEDIAN	[illegible]	STD DEV	7.343200E 00	M4	9.425465E 03	.10 QUANTILE	1.006444E 01
TRI-MEAN	[illegible]	COEF VAR	3.578218E-01	SKEWNESS	4.530017E-02	.25 QUANTILE (HINGE)	1.684367E 01
MIDMEAN	[illegible]	MEAN DEV	5.594054E 00	KURTOSIS	2.429905E-01	.50 QUANTILE (MEDIAN)	[illegible]
MIDRANGE	[illegible]	RANGE	3.458468E 01	BETA1	1.762011E 01	.75 QUANTILE (HINGE)	2.455625E 01
GEOM MEAN	[illegible]	MIDSPREAD	8.152573E 00	BETA2	9.072289E 03	.90 QUANTILE	2.871545E 01
HARM MEAN	[illegible]					MAXIMUM	[illegible]

STATS FOR OFFSET BETWEEN THE TWO POINTS

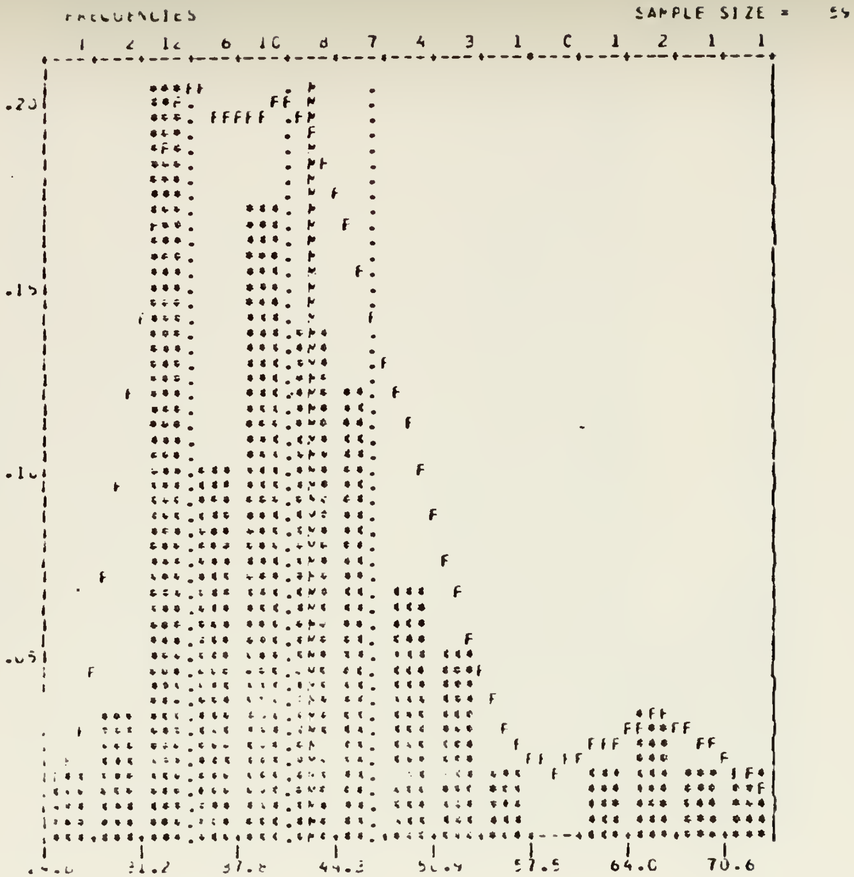
Day 126 Line 5



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	3.380159E 01	VARIANCE	9.376105E 01	M3	-2.292353E 02	MINIMUM	1.072420E 01
MEDIAN	3.434563E 01	STD DEV	9.683031E 00	M4	1.854527E 04	.10 QUANTILE	2.055377E 01
TRIMEAN	3.356040E 01	COEF VAR	2.864667E-01	SKEWNESS	-2.524920E-01	.25 QUANTILE (HINGE)	2.923460E 01
MIDMEAN	3.412981E 01	MEAN DEV	8.263928E 00	KURTOSIS	-8.904551E-01	.50 QUANTILE (MEDIAN)	3.434563E 01
MIDRANGE	3.042297E 01	RANGE	3.939754E 01	BETA1	-2.195047E 02	.75 QUANTILE (HINGE)	4.154775E 01
GEOM MEAN	3.227579E 01	MIDSPREAD	1.671315E 01	BETA2	1.622255E 04	.90 QUANTILE	4.570312E 01
HARM MEAN	3.059163E 01					MAXIMUM	5.012175E 01

STATS FOR OFFSET BETWEEN THE TWO POINTS

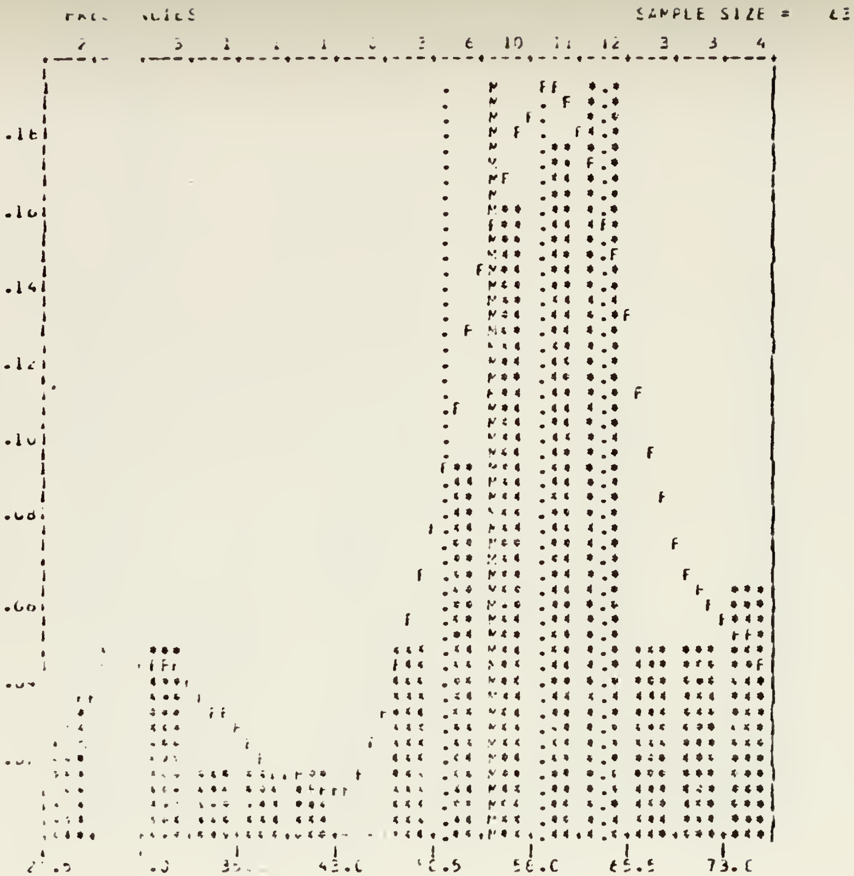
Day 126 Line 6



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	4.247940E 01	VARIANCE	1.031703E 02	M3	1.207501E 03	MINIMUM	2.462209E 01
MEDIAN	4.041112E 01	STD DEV	1.015728E 01	M4	4.475092E 04	.10 QUANTILE	3.211546E 01
TRIMEAN	4.043550E 01	COEF VAR	2.391100E-01	SKEWNESS	1.152273E 00	.25 QUANTILE (HINGE)	3.422504E 01
MIDMEAN	4.077303E 01	MEAN DEV	7.447092E 00	KURTOSIS	1.204292E 00	.50 QUANTILE (MEDIAN)	4.041112E 01
MIDRANGE	4.926350E 01	RANGE	4.928265E 01	BETA1	1.146757E 03	.75 QUANTILE (HINGE)	4.669478E 01
[illegible] MEAN	[illegible]	MIDSPREAD	1.246574E 01	BETA2	4.217261E 04	.90 QUANTILE	5.295117E 01
[illegible] MEAN	[illegible]					MAXIMUM	7.390454E 01

STATS FOR OFFSET BETWEEN THE TWO POINTS

Day 126 Line 7



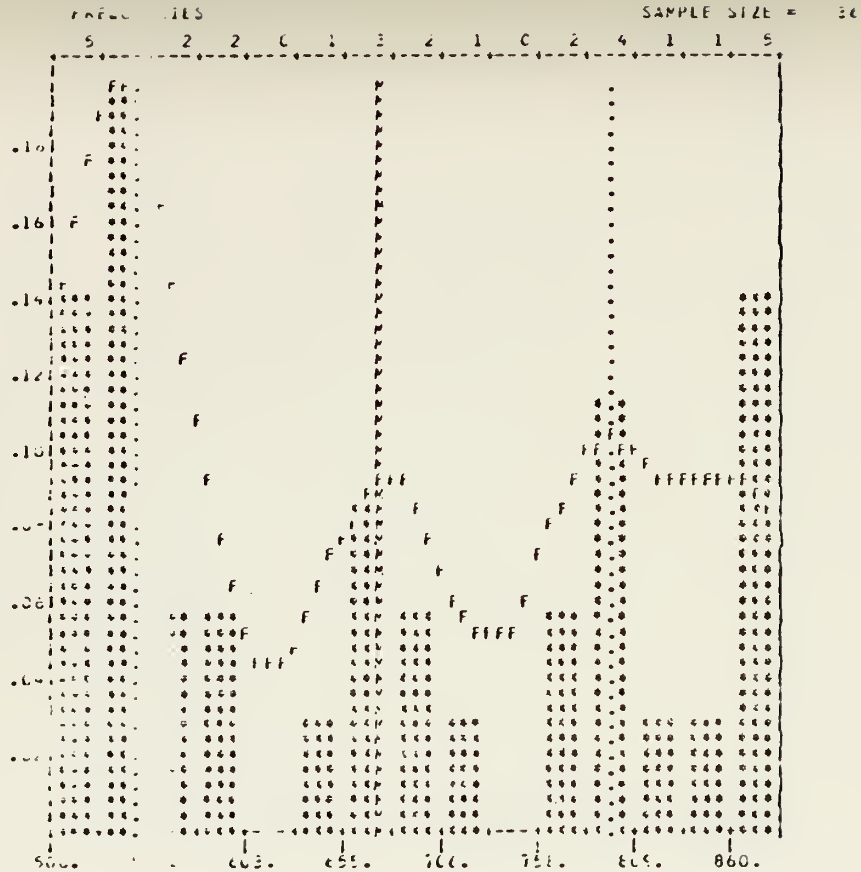
CENTRAL TENDENCY	
MEAN	5.5375[illegible]E 01
MEDIAN	[illegible] 01
TRIMEAN	[illegible] 01
MIDMEAN	[illegible] 01
MIDRANGE	[illegible] 01
GEOM MEAN	[illegible] 01
HARM MEAN	[illegible] 01

SPREAD		HIGHER CENTRAL MOMENTS	
VARIANCE	1.930167E 02	M3	-2.710058E 03
STD DEV	1.385[illegible]E 01	M4	1.227531E 05
COEF VAR	2.506851E-01	SKEWNESS	-1.010631E 00
MEAN DEV	[illegible]E 00	KURTOSIS	2.549009E-01
RANGE	5.623457E 01	BETA1	-2.562413E 03
MIDSPREAD	1.266588E 01	BETA2	1.184241E 05

DISTRIBUTION		
MINIMUM		[illegible] 01
.10 QUANTILE		3.0247[illegible] 01
.25 QUANTILE	(HINGE)	[illegible] 01
.50 QUANTILE	(MEDIAN)	5.[illegible] 01
.75 QUANTILE	(HINGE)	6.4[illegible]375E 01
.90 QUANTILE		6.[illegible] 01
MAXIMUM		7.675792E 01

STATS FOR OFFSET BETWEEN THE TWO POINTS

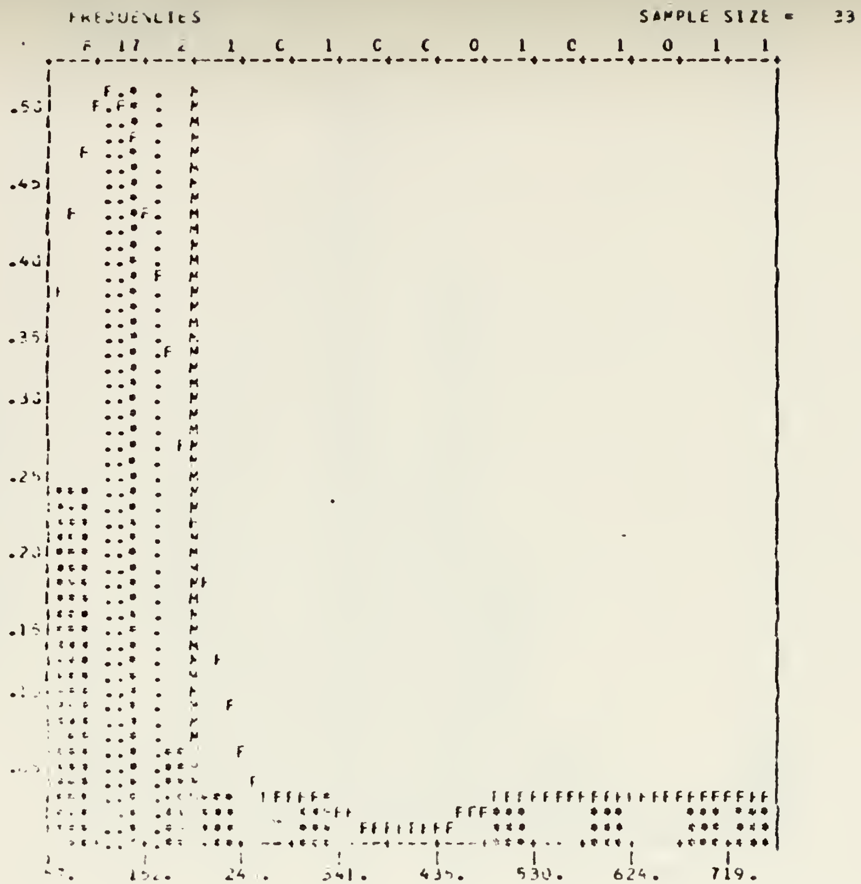
Day 126 Line 8



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	6.713447E 02	VARIANCE	1.786666E 04	M3	5.675161E 05	MINIMUM	5.002254E 02
MEDIAN	.709514E 02	STD DEV	1.336433E 02	M4	4.635350E 08	.10 QUANTILE	5.152756E 02
TRIMEAN	.702053E 02	COEF VAR	1.990687E-01	SKEWNESS	2.461360E-01	.25 QUANTILE (HINGE)	5.420303E 02
MIDMEAN	.577266E 02	MEAN DEV	1.173448E 02	KURTOSIS	-1.545672E 00	.50 QUANTILE (MEDIAN)	6.709514E 02
MIDRANGE	.832615E 02	RANGE	3.656723E 02	BETA1	5.354653E 05	.75 QUANTILE (HINGE)	7.970083E 02
GEOM MEAN	.565064E 02	MIDSPREAD	2.549785E 02	BETA2	4.633185E 08	.90 QUANTILE	8.645160E 02
HARM MEAN	.619512 02					MAXIMUM	8.661575E 02

STATS FOR [illegible] SET BETWEEN THE TWO POINTS

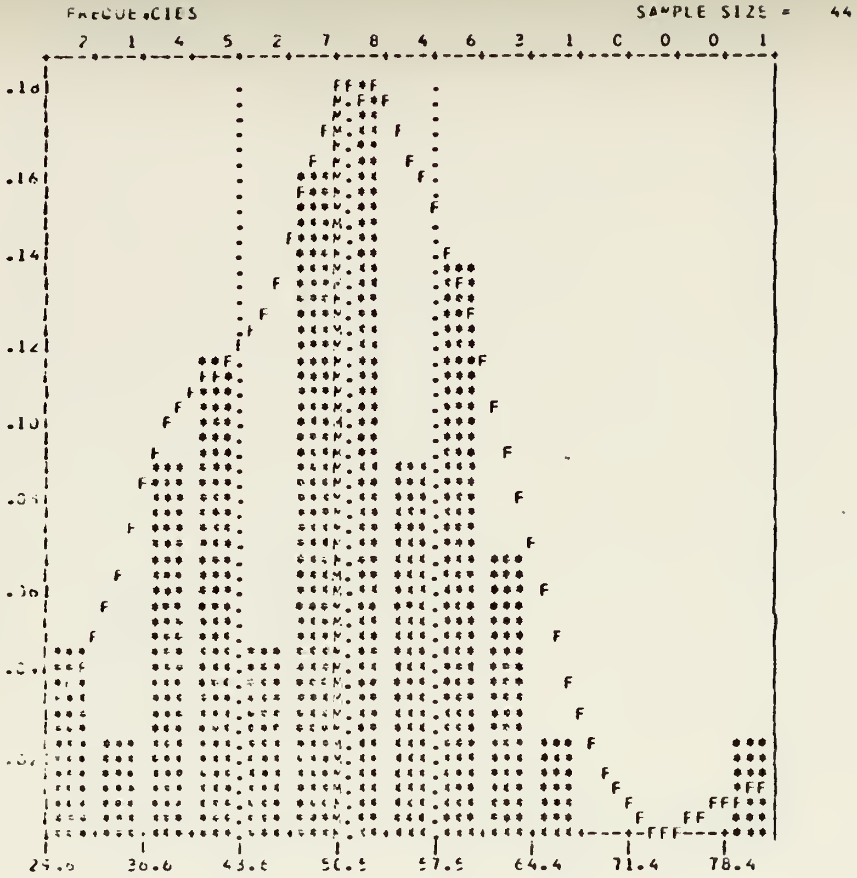
Day 127 Line 1



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	1.874773E 02	VARIANCE	3.125205E 04	M3	1.304145E 07	MINIMUM	5.699374E 01
MEDIAN	1.232929E 02	STD DEV	1.767826E 02	M4	6.900318E 09	.10 QUANTILE	8.437581E 01
TRIMEAN	1.262562E 02	COEF VAR	9.429545E-01	SKEWNESS	2.360518E 00	.25 QUANTILE (HINGE)	1.022651E 02
MI MEAN	1.244411E 02	MEAN DEV	8.749545E 01	KURTOSIS	4.064583E 00	.50 QUANTILE (MEDIAN)	1.232929E 02
MIDRANGE	4.114106E 02	RANGE	7.088337E 02	BETA1	1.167583E 07	.75 QUANTILE (HINGE)	1.563422E 02
GEOM MEAN	1.461960E 02	MIDSPREAD	5.407706E 01	BETA2	6.234317E 09	.90 QUANTILE	3.162561E 02
HARM MEAN	1.267456E 02					MAXIMUM	7.658276E 02

STATS FOR OFFSET BETWEEN THE TWO POINTS

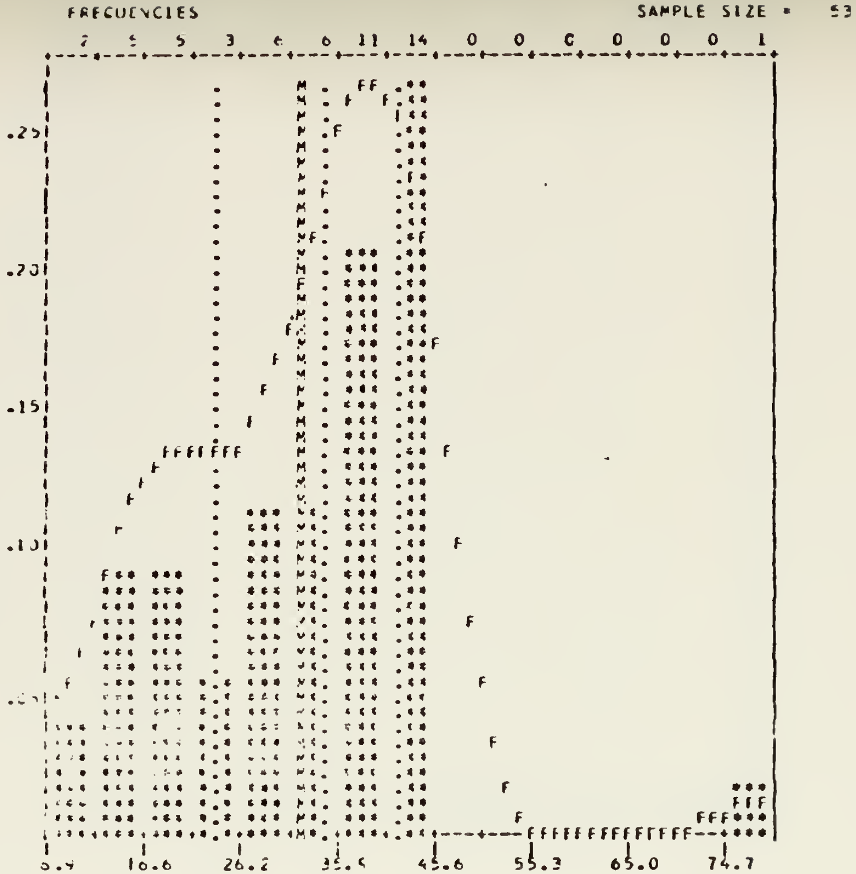
Day 127 Line 2



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	5.057520E 01	VARIANCE	1.048692E 02	M3	3.351140E 02	MINIMUM	2.963731E 01
MEDIAN	5.082863E 01	STD DEV	1.024057E 01	M4	4.008069E 04	.10 QUANTILE	3.676731E 01
TRIMEAN	5.349692E 01	COEF VAR	2.024820E-01	SKEWNESS	3.157722E-01	.25 QUANTILE (HINGE)	4.292072E 01
MIDMEAN	5.302164E 01	MEAN DEV	7.852922E 00	KURTOSIS	6.445131E-01	.50 QUANTILE (MEDIAN)	5.082863E 01
MIDRANGE	5.574255E 01	RANGE	5.221054E 01	BETA1	3.163430E 02	.75 QUANTILE (HINGE)	5.741769E 01
GEOM.MEAN	4.954848E 01	MIDSPREAD	1.449658E 01	BETA2	3.788692E 04	.90 QUANTILE	6.600438E 01
HARM MEAN	4.846922E 01					MAXIMUM	8.184765E 01

STATS FOR OFFSET BETWEEN THE TWO POINTS

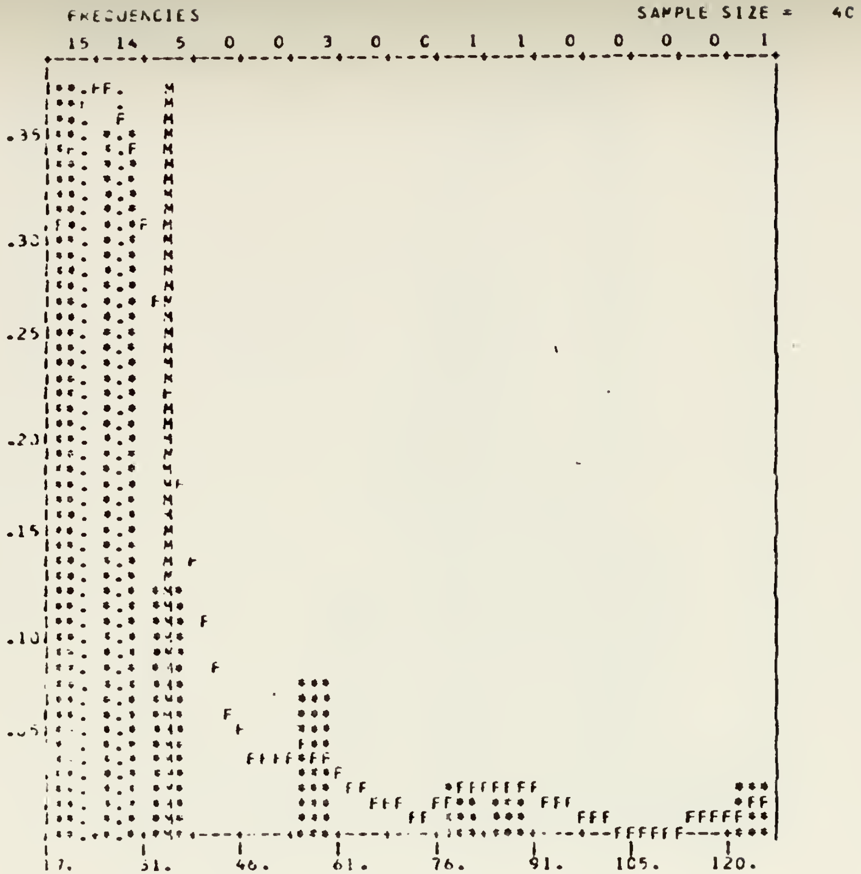
Day 127 Line 3



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION		
MEAN	3.242133E 01	VARIANCE	1.598329E 02	M3	1.007837E 03	MINIMUM		6.860129E 00
MEDIAN	3.504155E 01	STD DEV	1.264250E 01	M4	1.324787E 05	.10 QUANTILE		1.533679E 01
TRIMEAN	3.357359E 01	COEF VAR	3.655441E-01	SKEWNESS	4.987994E-01	.25 QUANTILE	(HINGE)	2.255054E 01
MIDMEAN	3.368999E 01	MEAN DEV	9.698647E 00	KURTOSIS	2.185774E 00	.50 QUANTILE	(MEDIAN)	3.504155E 01
MIDRANGE	4.320294E 01	RANGE	7.268564E 01	BETA1	9.515078E 02	.75 QUANTILE	(HINGE)	4.166078E 01
GEOM MEAN	2.959624E 01	MIDSPREAD	1.911024E 01	BETA2	1.252540E 05	.90 QUANTILE		4.374628E 01
HARM MEAN	2.601483E 01					MAXIMUM		7.554578E 01

STATS FOR OFFSET BETWEEN THE TWO POINTS

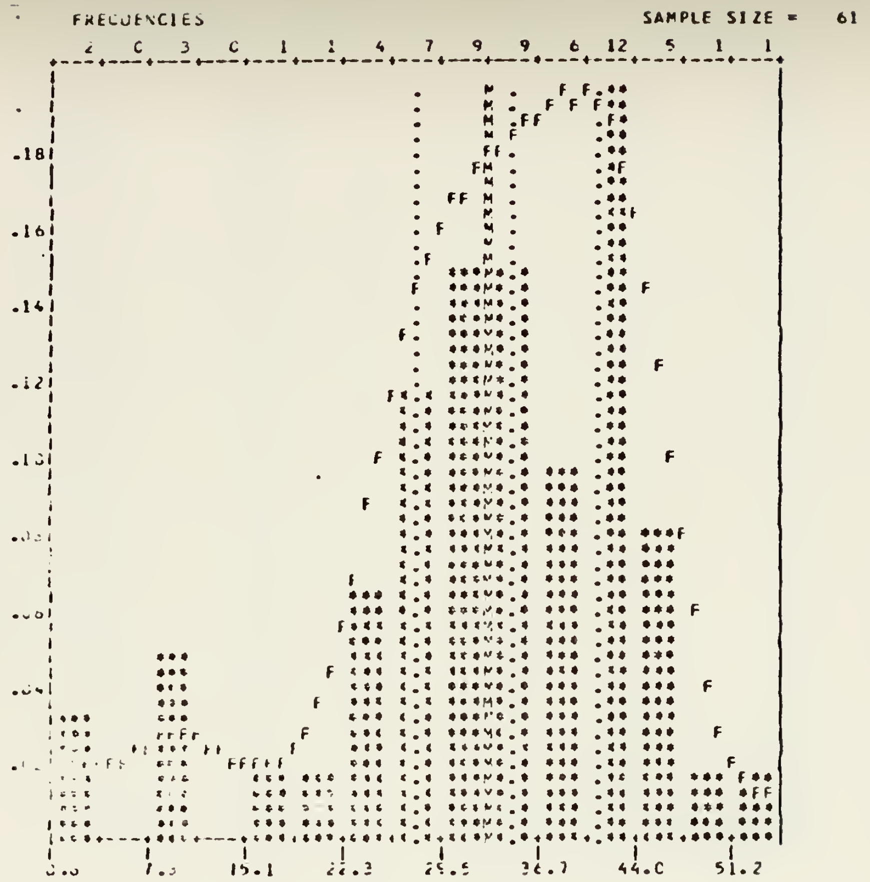
Day 127 Line 4



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	3.312619E 01	VARIANCE	4.900818E 02	M3	3.051246E 04	MINIMUM	1.670053E 01
MEDIAN	2.536580E 01	STD DEV	2.213779E 01	M4	2.636112E 06	.10 QUANTILE	1.808423E 01
TRIMEAN	2.669620E 01	COEF VAR	6.682462E-01	SKEWNESS	2.812394E 00	.25 QUANTILE (HINGE)	2.100447E 01
MIDMEAN	2.659433E 01	MEAN DEV	1.174965E 01	KURTOSIS	7.575562E 00	.50 QUANTILE (MEDIAN)	2.636590E 01
MIDRANGE	7.209071E 01	RANGE	1.107804E 02	BETA1	2.826219E 04	.75 QUANTILE (HINGE)	3.304877E 01
GEOM MEAN	2.927955E 01	MIDSPREAD	1.204430E 01	BETA2	2.407392E 06	.90 QUANTILE	5.452256E 01
HARM MEAN	2.672247E 01					MAXIMUM	1.274809E 02

STATS FOR OFFSET BETWEEN THE TWO POINTS

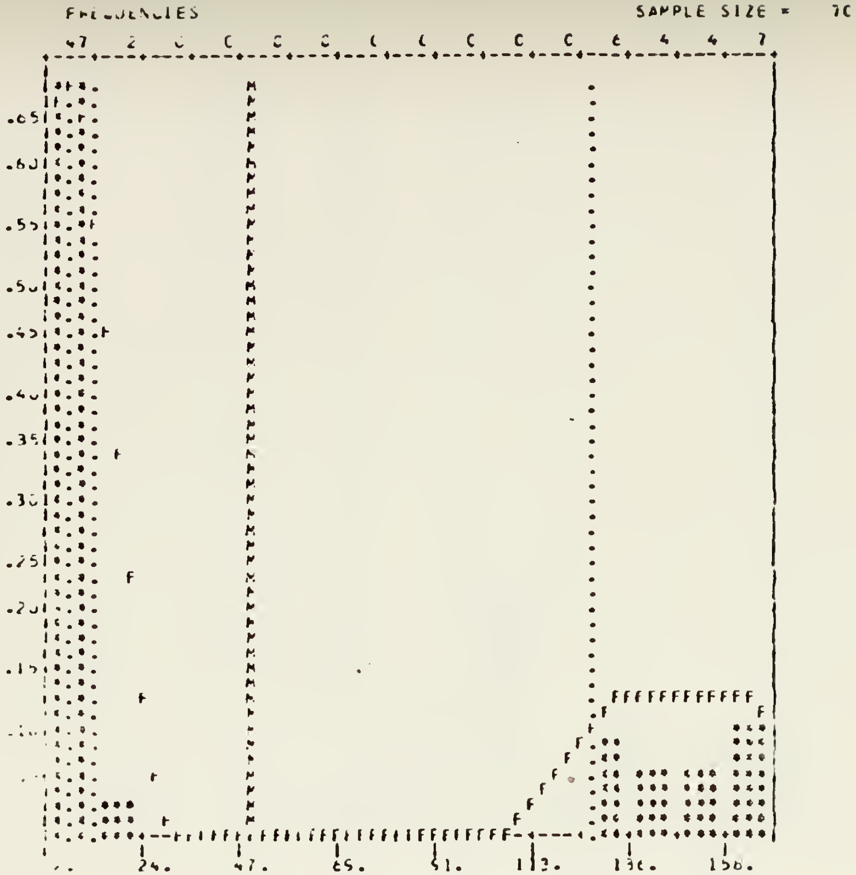
Day 127 Line 5



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION		
MEAN	3.324766E 01	VARIANCE	1.227934E 02	M3	-1.485193E 03	MINIMUM		6.027549E-01
MEDIAN	3.532109E 01	STD DEV	1.108122E 01	M4	6.356545E 04	.10 QUANTILE		1.640377E 01
TRIMEAN	3.504230E 01	COEF VAR	3.332911E-01	SKEWNESS	-1.094431E 00	.25 QUANTILE	(HINGE)	2.770174E 01
MIDMEAN	3.438647E 01	MEAN DEV	8.183216E 00	KURTOSIS	1.242568E 00	.50 QUANTILE	(MEDIAN)	3.532109E 01
MIDRANGE	2.770439E 01	RANGE	5.420119E 01	BETA1	-1.416756E 03	.75 QUANTILE	(HINGE)	4.182527E 01
GEOM MEAN	2.859795E 01	MIDSPREAD	1.412349E 01	BETA2	6.122726E 04	.90 QUANTILE		4.354378E 01
HARM MEAN	1.363339E 01					MAXIMUM		5.480459E 01

STATS FOR OFFSET BETWEEN THE TWO POINTS

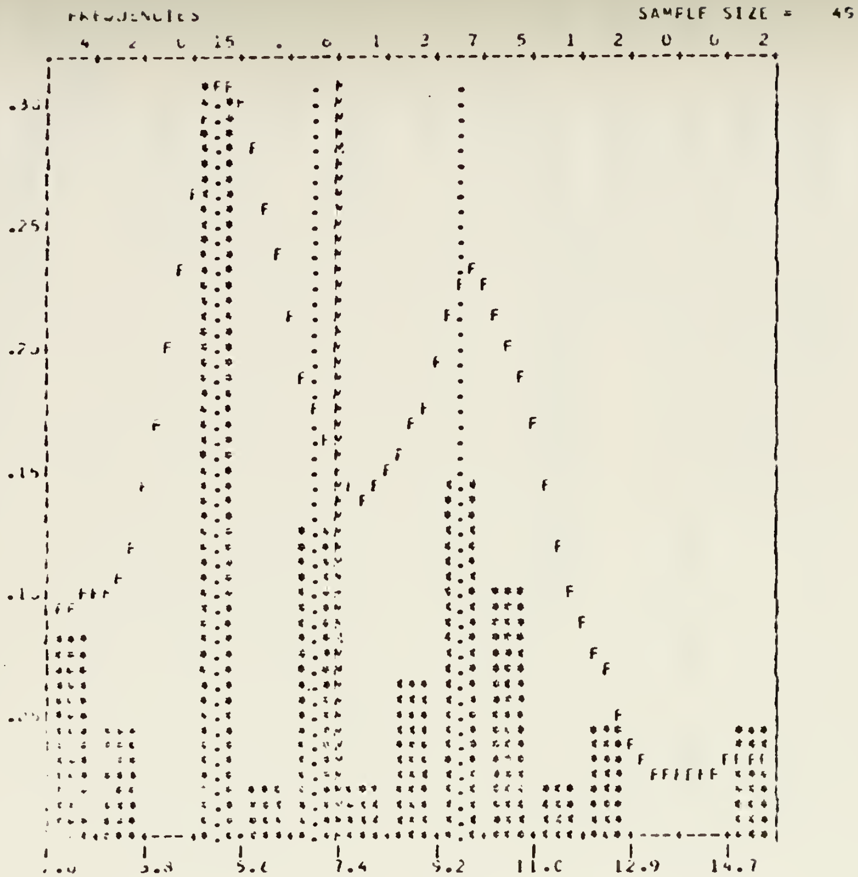
Day 127 Line 6



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	4.938129E 01	VARIANCE	4.240762E 03	M3	2.593282E 05	MINIMUM	1.962578E 00
MEDIAN	5.825407E 00	STD DEV	6.512112E 01	M4	3.406317E 07	.10 QUANTILE	4.784321E 00
TRIMEAN	3.833121E 01	COEF VAR	1.318741E 00	SKEWNESS	9.356407E-01	.25 QUANTILE (HINGE)	5.907520E 00
MIDMEAN	2.218777E 01	MEAN DEV	4.352992E 01	KURTOSIS	-1.105524E 00	.50 QUANTILE (MEDIAN)	5.825407E 00
MIDRANGE	8.501605E 01	RANGE	1.672665E 02	BETA1	2.483201E 05	.75 QUANTILE (HINGE)	1.281582E 02
GEOM MEAN	1.567661E 01	MIDSPREAD	1.226504E 02	BETA2	3.362515E 07	.90 QUANTILE	1.534165E 02
HARM MEAN	3.254754E 00					MAXIMUM	1.692511E 02

STATS FOR OFFSET BETWEEN THE TWO POINTS

Day 128 Line 1



CENTRAL TENDENCY		SPREAD		HIGHER CENTRAL MOMENTS		DISTRIBUTION	
MEAN	7.425543E 00	VARIANCE	1.045137E 01	M3	1.356576E 01	MINIMUM	1.562578E 00
MEDIAN	6.970473E 00	STD DEV	3.232855E 00	M4	2.832056E 02	.10 QUANTILE	2.877575E 00
TRIMEAN	7.207508E 00	COEF VAR	4.351116E-01	SKEWNESS	4.133387E-01	.25 QUANTILE (HINGE)	5.055625E 00
MIDMEAN	7.155450E 00	MEAN DEV	2.666531E 00	KURTOSIS	-4.072714E-01	.50 QUANTILE (MEDIAN)	6.970473E 00
MIDRANGE	8.781155E 00	RANGE	1.355717E 01	BETA1	1.312235E 01	.75 QUANTILE (HINGE)	9.829407E 00
GEOM MEAN	6.068254E 00	MIDSPREAD	4.765722E 00	BETA2	2.730564E 02	.90 QUANTILE	1.094757E 01
HARM MEAN	5.076705E 00					MAXIMUM	1.557975E 01

STATS FOR OFFSET BETWEEN THE TWO POINTS

Day 128 Line 2

APPENDIX J: GLOSSARY

bps - bits per second

C/A - coarse acquisition

CDU - Control Display Unit
CGS - Coast and Geodetic Survey
CS - Control Segment

dB - deciBel

dBM - deciBel re 1 milliwatt

dBW - deciBel re 1 Watt

DMA - Defense Mapping Agency

EPE - Estimated Position Error

fps - feet per second

GDOP - Geometric Dilution of Precision

GHz - GigiHertz

GP - Geographic Position

GPS - Global Positioning System

HDOP- Dilution of precision in 2 horizontal dimensions

HOW - Handover word

H/TC - Hydrographic/Topographic Center

Hz - Hertz

in - inch

km - kilometer

Kt - knot

Lat - Latitude

Long - Longitude

m - meter
mb - millibar
MB4 - Monterey Bay 4

Mbps - Migabits per second

MCS - Master Control Station

MHz - MegaHertz

mm - millimeter

mps - meters per second

MRS III - Mini-Ranger III Positioning Determining System

m/s - meter per second

MS - Monitor Station

MVUE - Manpack/Vehicular User Equipment

NAD-27 - North American Datum 1927

NAVOCEANO - Naval Oceanographic Office

NAVSTAR - NAVigation Satellite Timing and Ranging

nmi - Nautical Mile

NNSS - Navy Navigation Satellite System

NOAA - National Oceanic and Atmospheric Administration

NPS - Naval Postgraduate School

NRL - Naval Research Laboratory

P-Code - Precision Code

PDOP - Position (in three dimensions), dilution of precision

PN - Psuedo-noise

PRN - Psuedo-random noise

RF - Radio Frequency

RMS - Root Mean Square

RSS - Root Sum Square

R/V - Research/Vessel

SAMSO - Space and Missile System Office

SS4 - Seaside 4

SV - Space Vehicle (satellite)

TDOP - Time, dilution of precision

TEC - Total electron count

TI - Texas Instruments Inc.

TIMATION - TIMe navigaTION

TIV - Two-in-view

TLM - Telemetry word

TTFF - Time to First Fix

UE - User Equipment

UERE - User Equipment Range Error

UERRE - User Equipment Range Rate Error

ULS - Upload Station

URE - User Range Error

UTM - Universal Transverse Mercator

USGE - U.S. Geological Survey

VDOP - Vertical dimension, dilution of precision

WGS-72 - World Geodetic System 1972

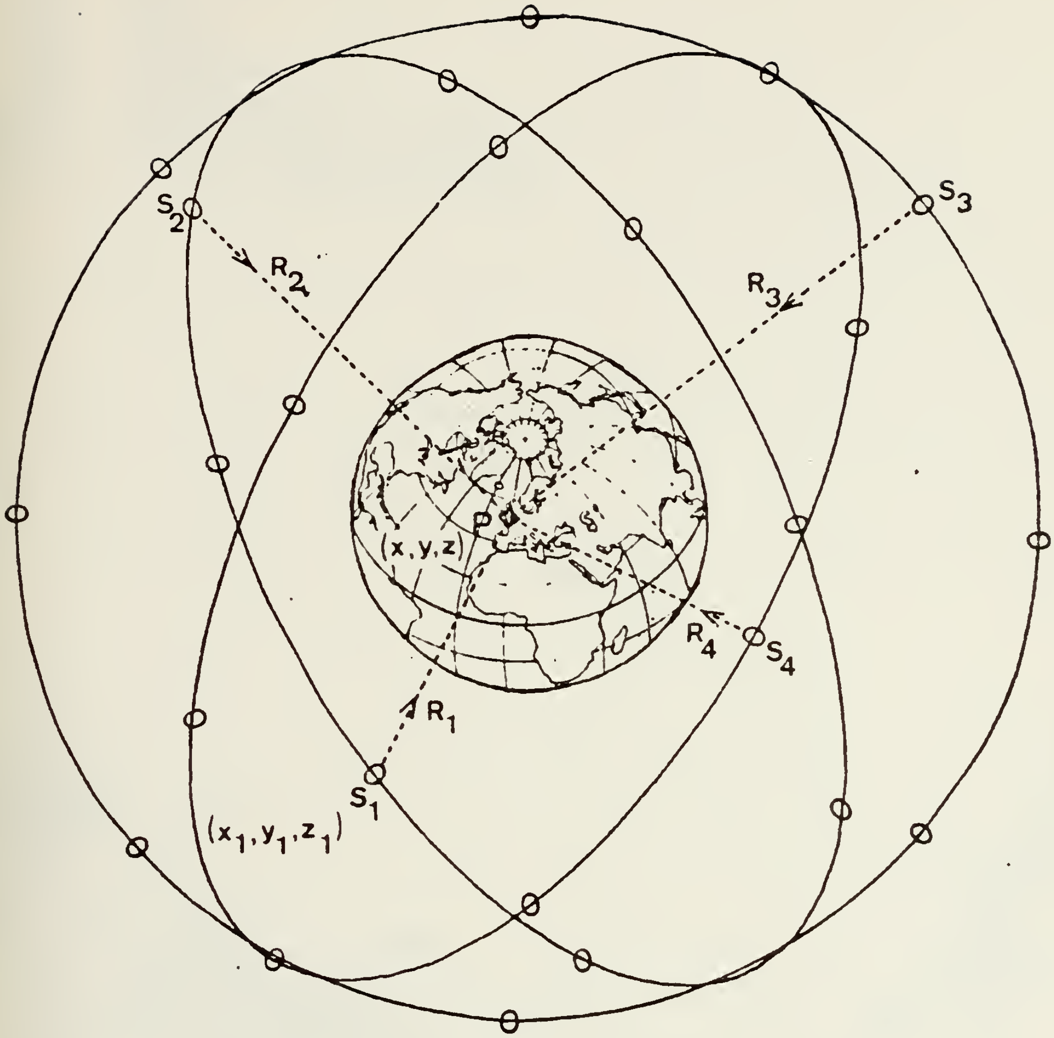


Figure 1. GPS Earth Centered Coordinate System

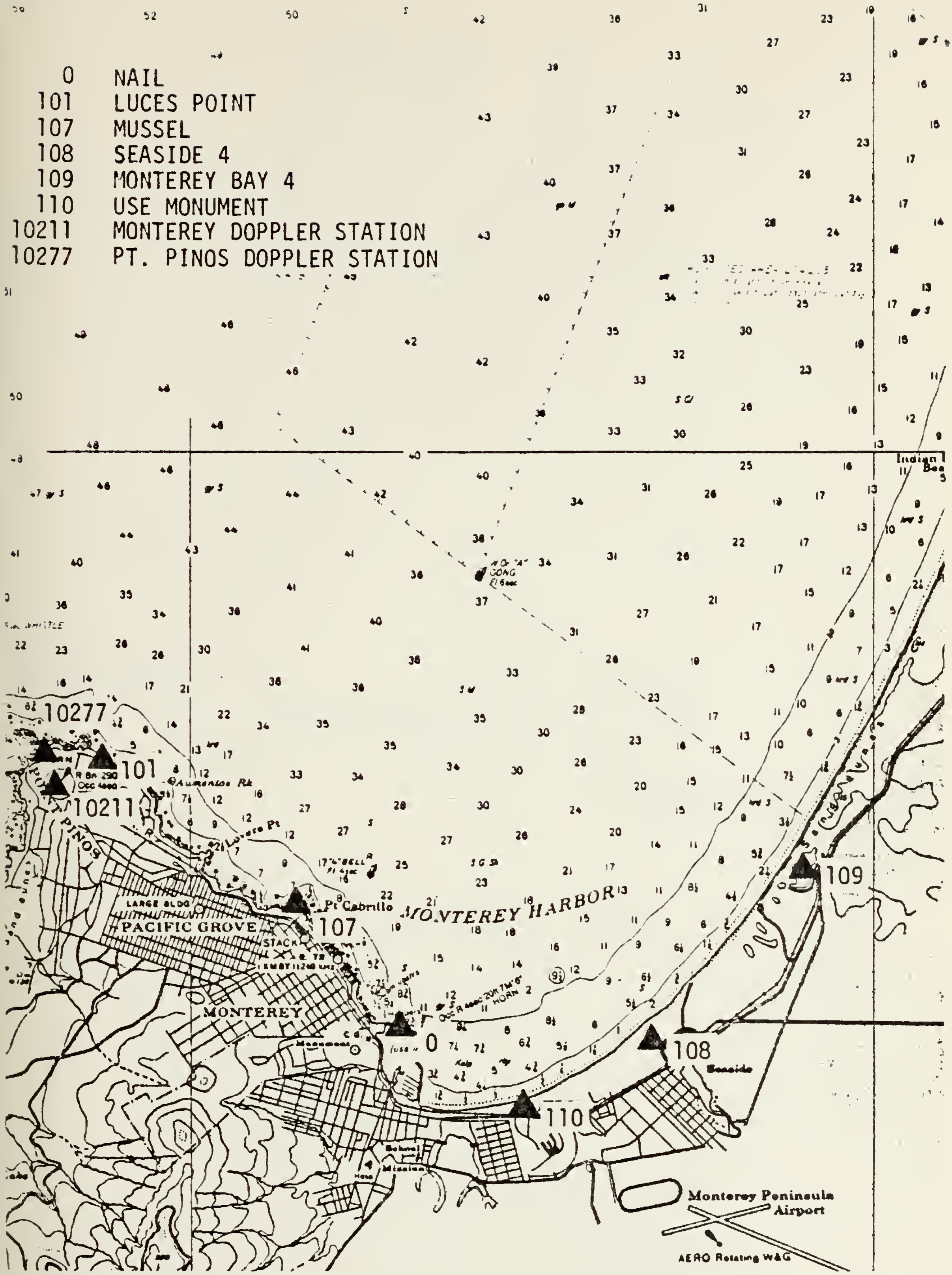
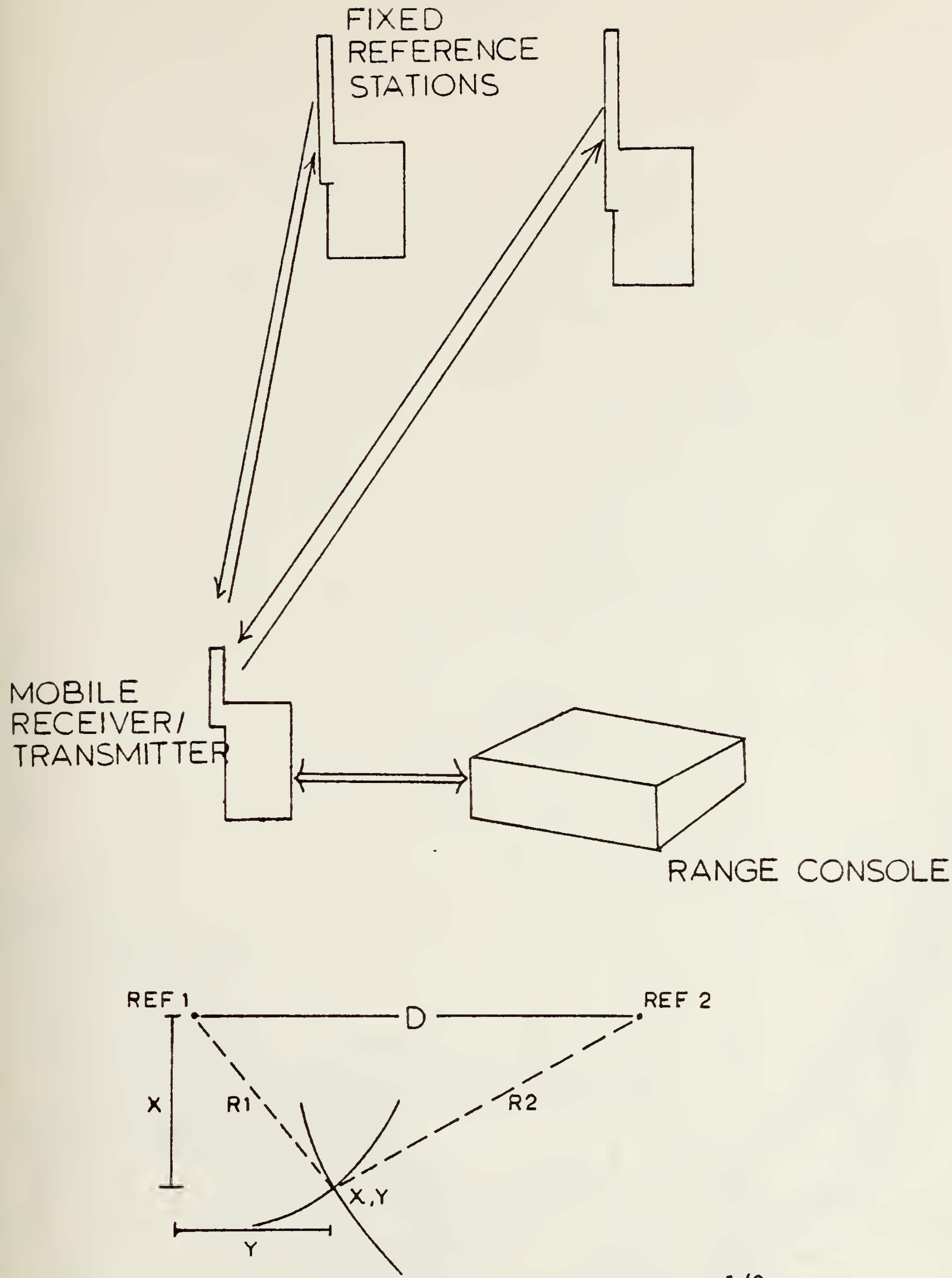


Figure 2. Geodetic Control Stations



$$X^2 - Y^2 = R_1^2 \qquad X = (R_1^2 - Y^2)^{1/2}$$

$$(X - D)^2 - Y^2 = R_2^2 \qquad Y = \frac{(D^2 - R_2^2 - R_1^2}{2D}$$

Figure 3. Mini Ranger III Trilateration (Two-Dimensional Geometry Example). [General Dynamics GPS-GD-209-1-CS-79-05, 1979]

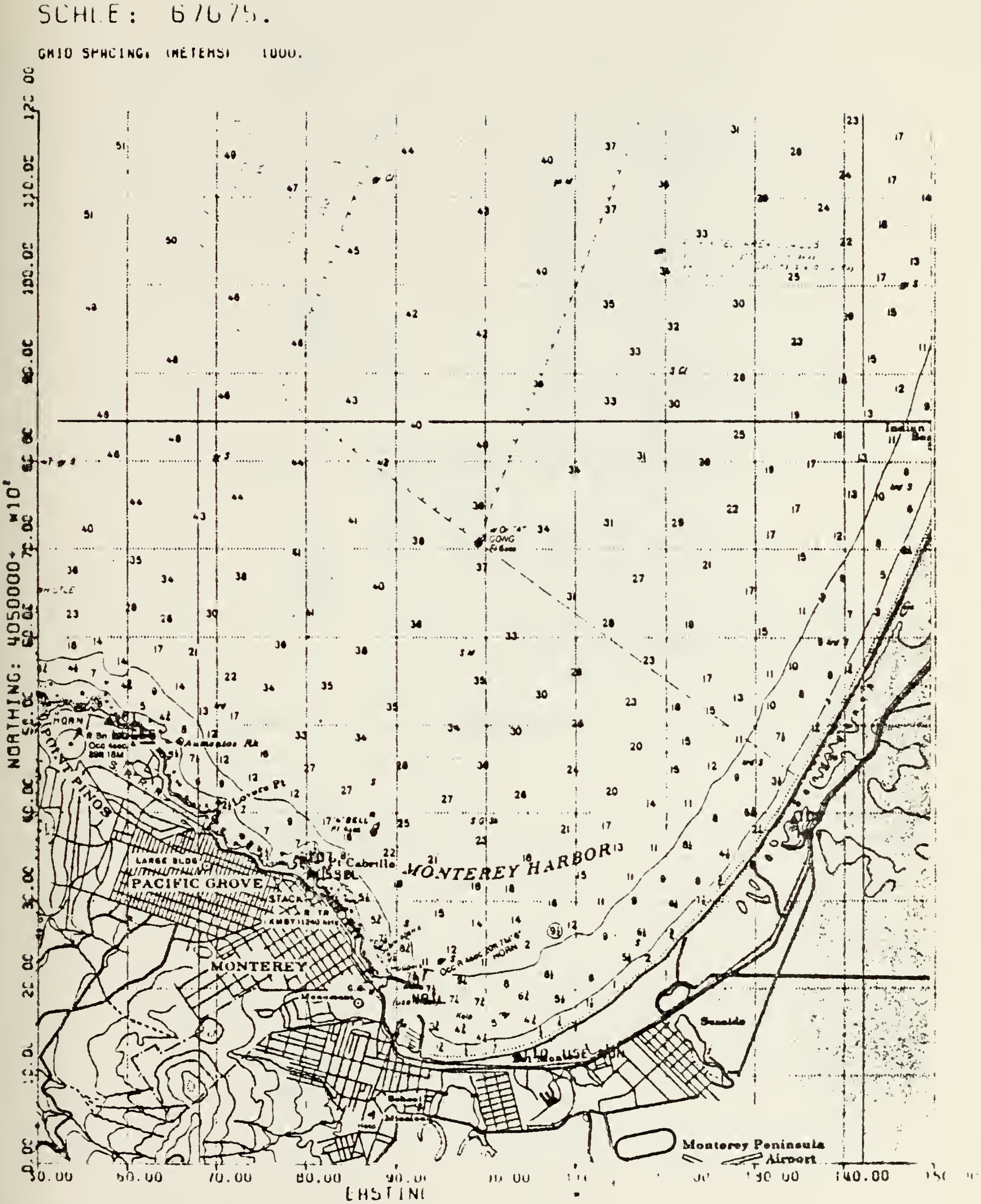
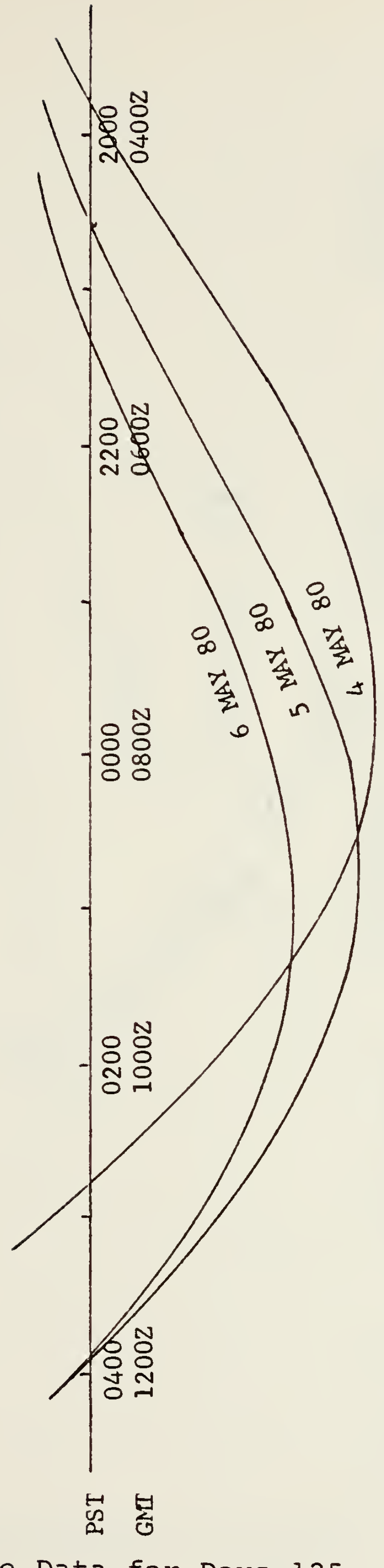
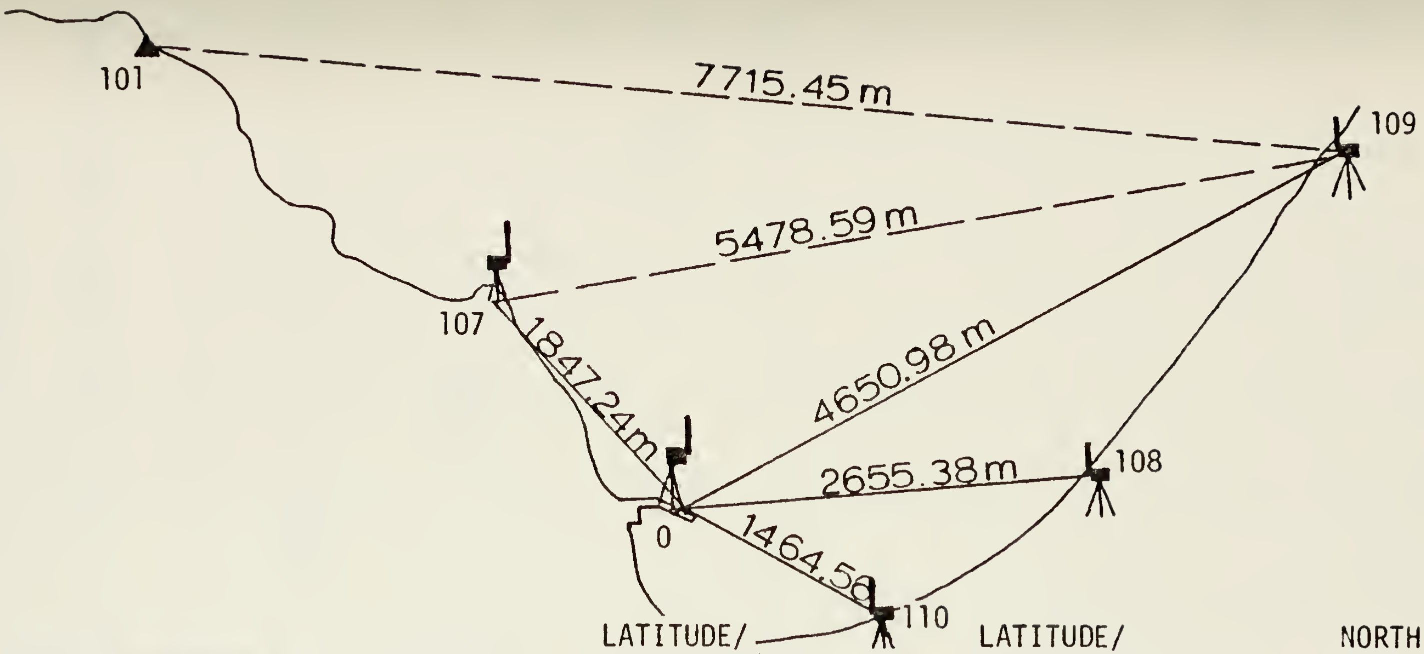


Figure 4. Operating Area with Universal Transverse Mercator Coordinates



DAY	DATE	TIME (GMT)	TIDE RANGE	
125	4 MAY 80	0540-0920	-1.15' to -1.84'	.69'
126	5 MAY 80	0558-1007	-.72' to -1.68'	.96'
127	6 MAY 80	0646-0915	-.7' to -1.29'	.59'

Figure 5. Tide Data for Days 125, 126 and 127



STATION NAME	STATION NUMBER	LATITUDE/ LONGITUDE(NAD-27)	LATITUDE/ LONGITUDE(WGS-72)	NORTHING/ EASTING(WGS-72)
NAIL	0	36°36'31".9530 N 121°53'25".1560 W	36°36'31".5279 N 121°53'29".2450 W	4052042.934 N 599138.621 E
MUSSEL	107	36°37'18".1510 N 121°54'11".6280 W	36°37'17".7244 N 121°54'15".7188 W	4053453.207 N 597967.837 E
MONTEREY BAY 4	109	36°37'31".1283 N 121°50'31".7275 W	36°37'30".7035 N 121°50'35".8133 W	4053917.206 N 603425.230 E
LUCES POINT	101	36°38'10".5240 N 121°55'38".3990 W	36°38'10".0954 N 121°55'42".4926 W	4055042.670 N 595794.472 E
USE MON	110	36°36' 4".6860 N 121°52'35".9040 W	36°36' 4".2620 N 121°52'39".9914 W	4051216.957 N 600372.042 E
SEASIDE 4	108	36°36'23".446 N 121°51'38".833 W		

Figure 6. Geodetic Control Stations, Baselines and Coordinates

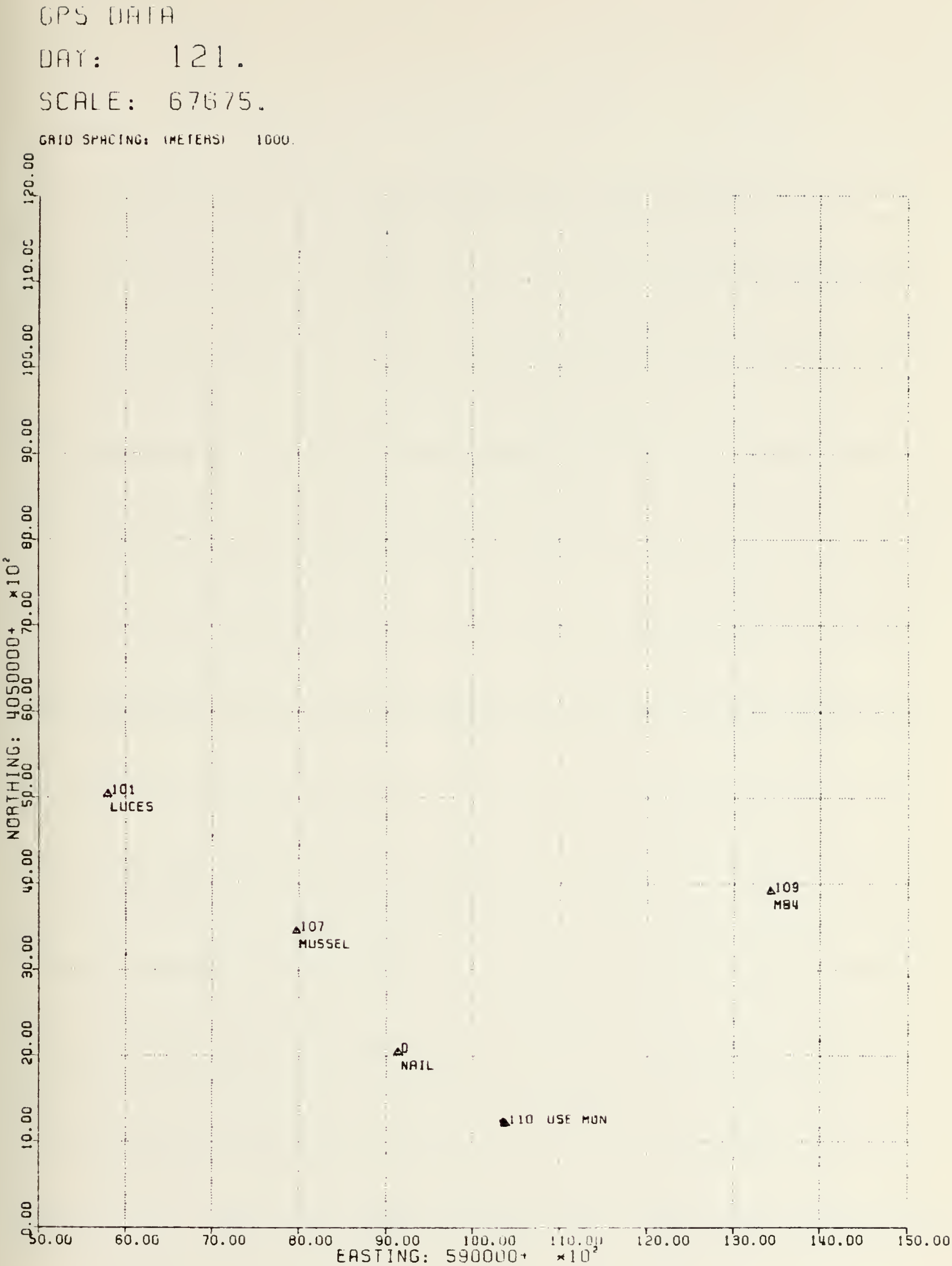


Figure 7. Beach Test Day 121

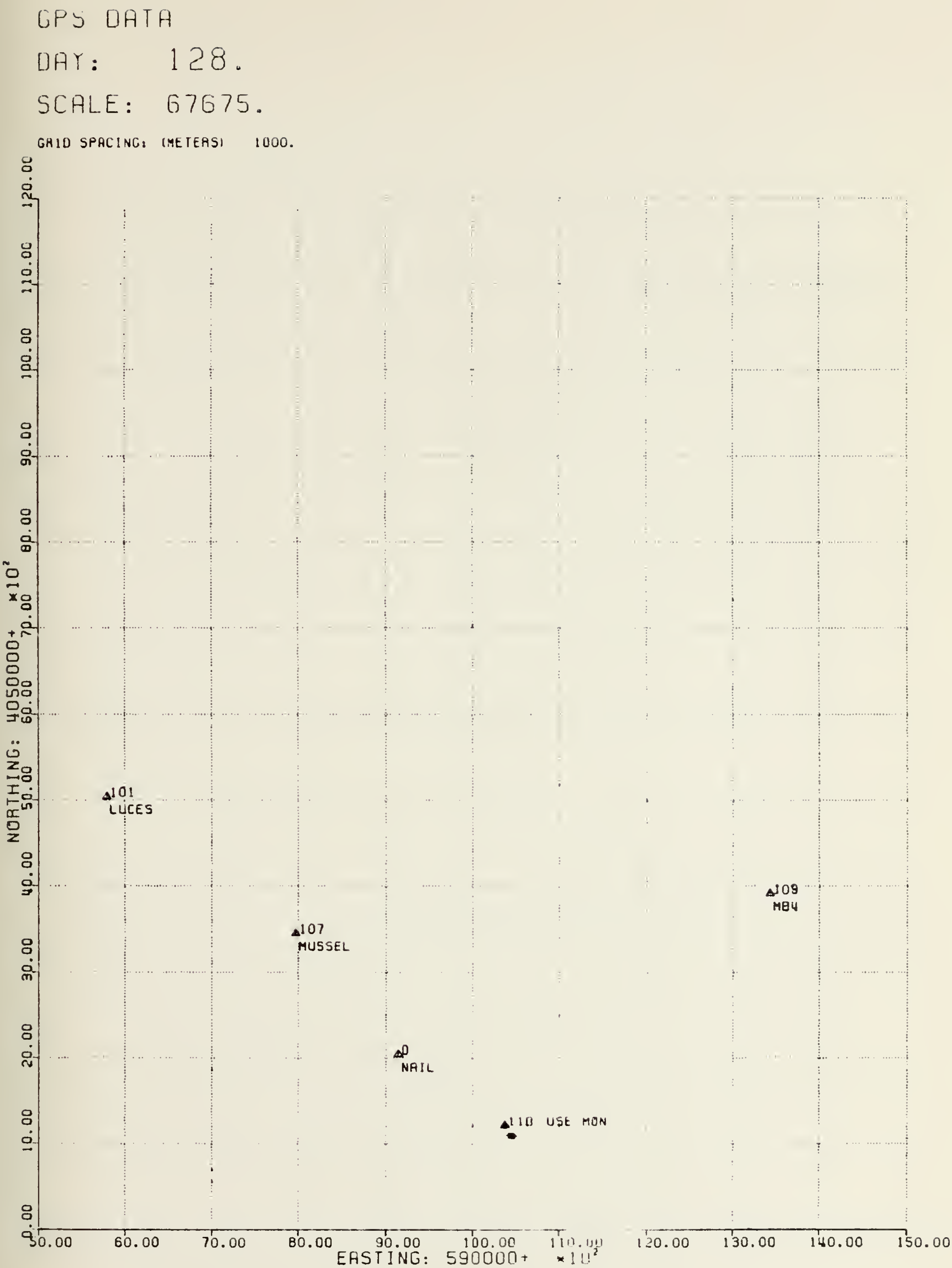


Figure 8. Beach Test Day 128

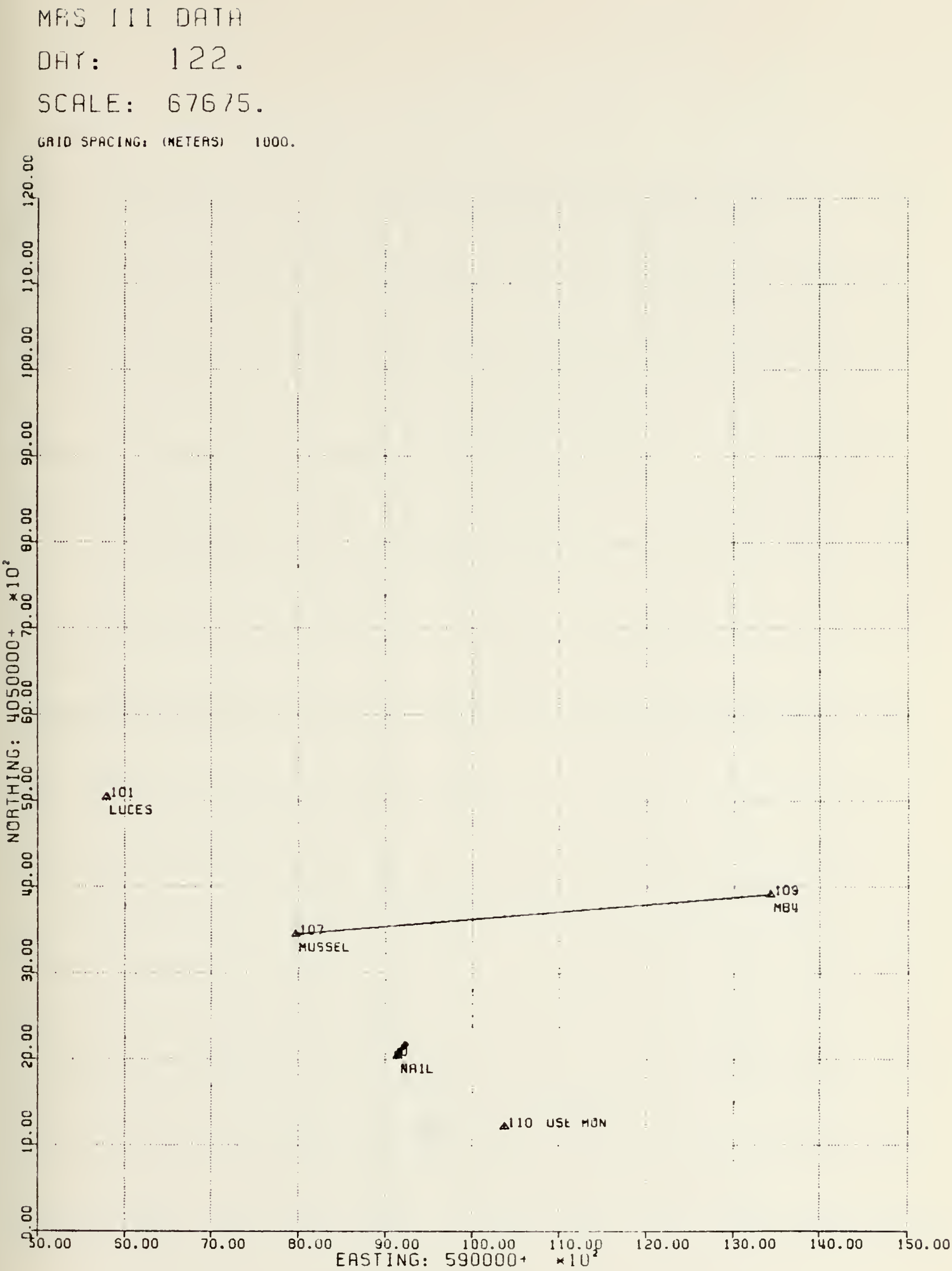


Figure 9. Pier Test (MRS III Data)

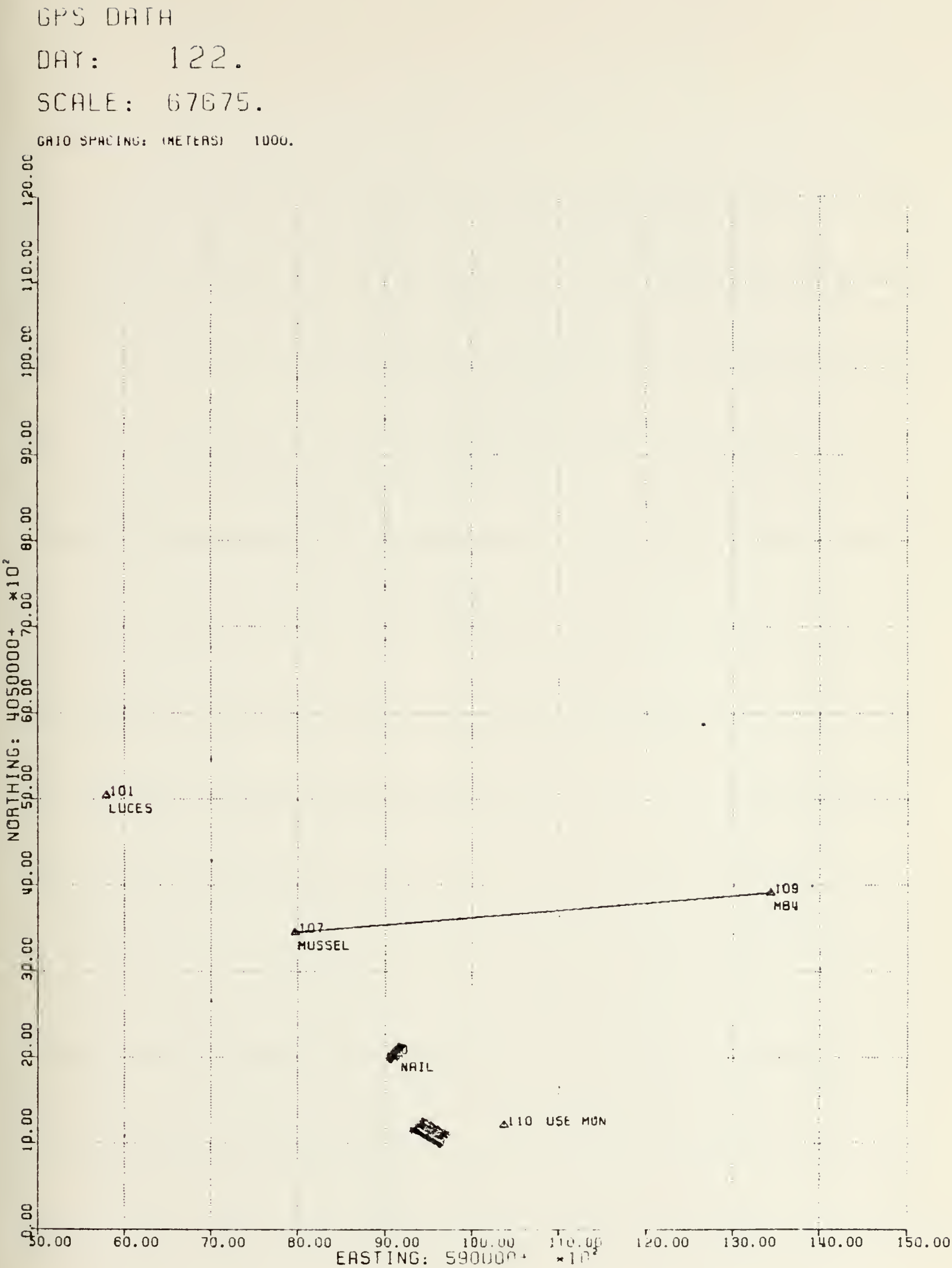


Figure 10. Pier Test

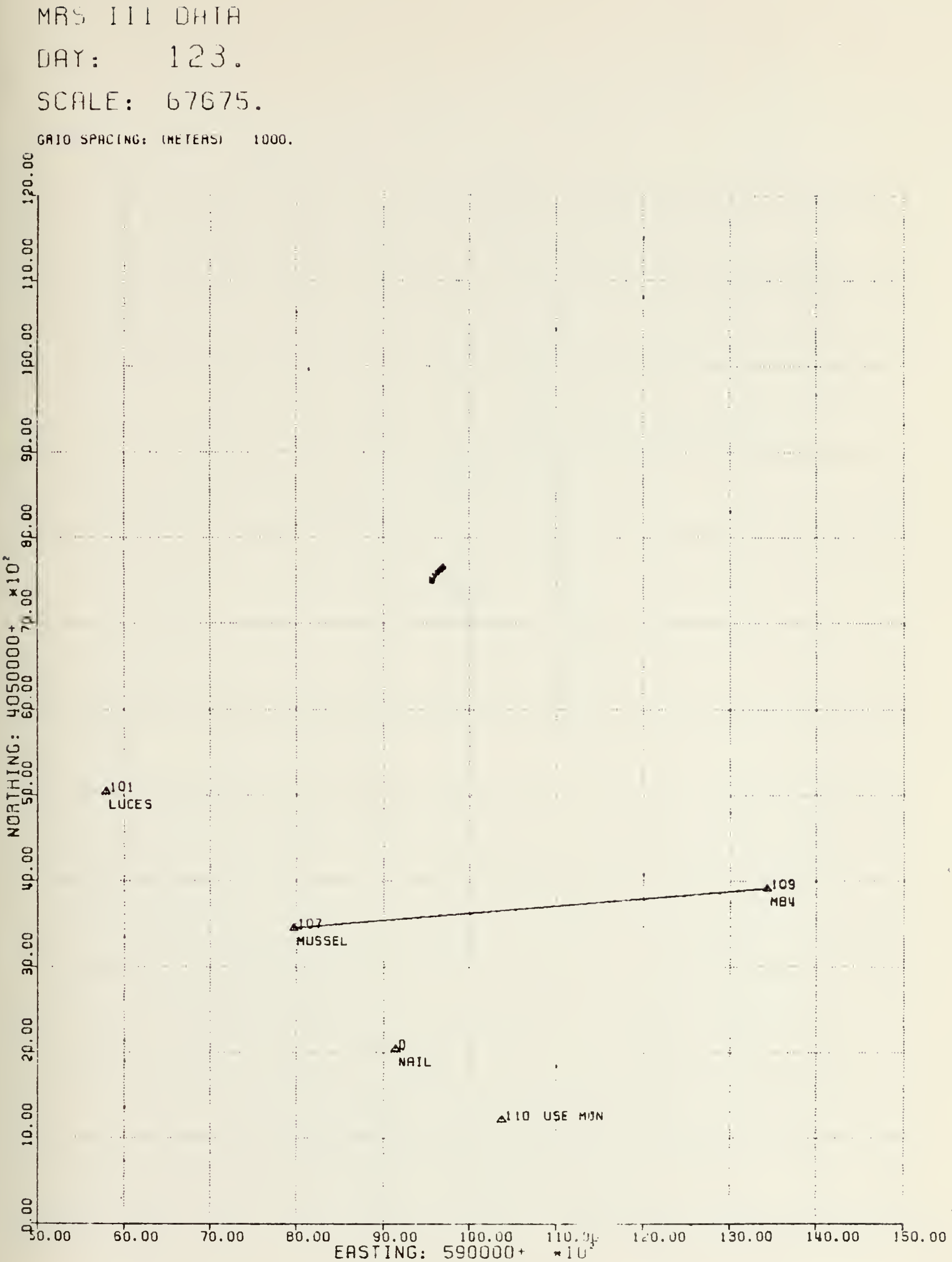


Figure 11. Anchor Test

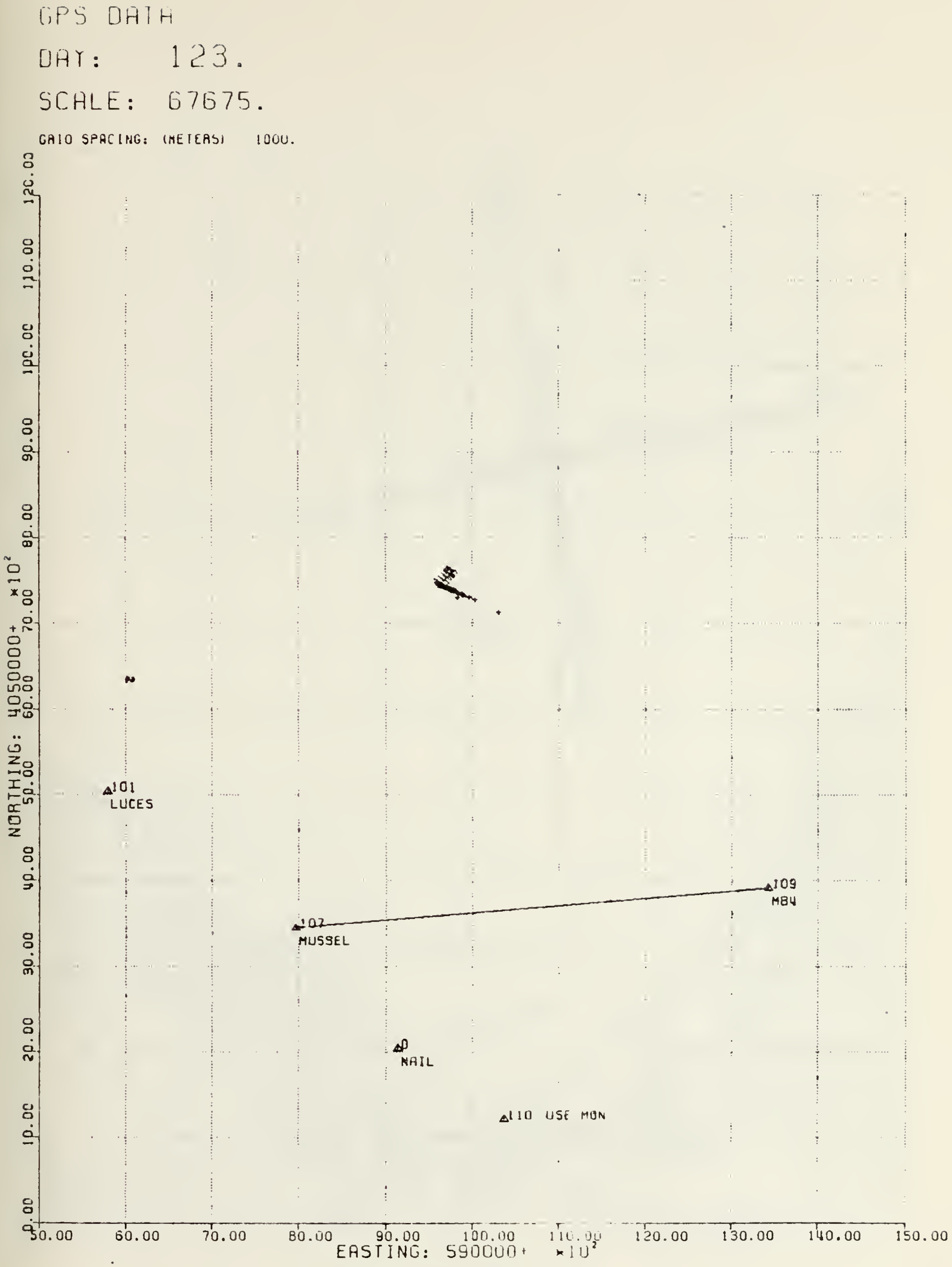


Figure 12. Anchor Test

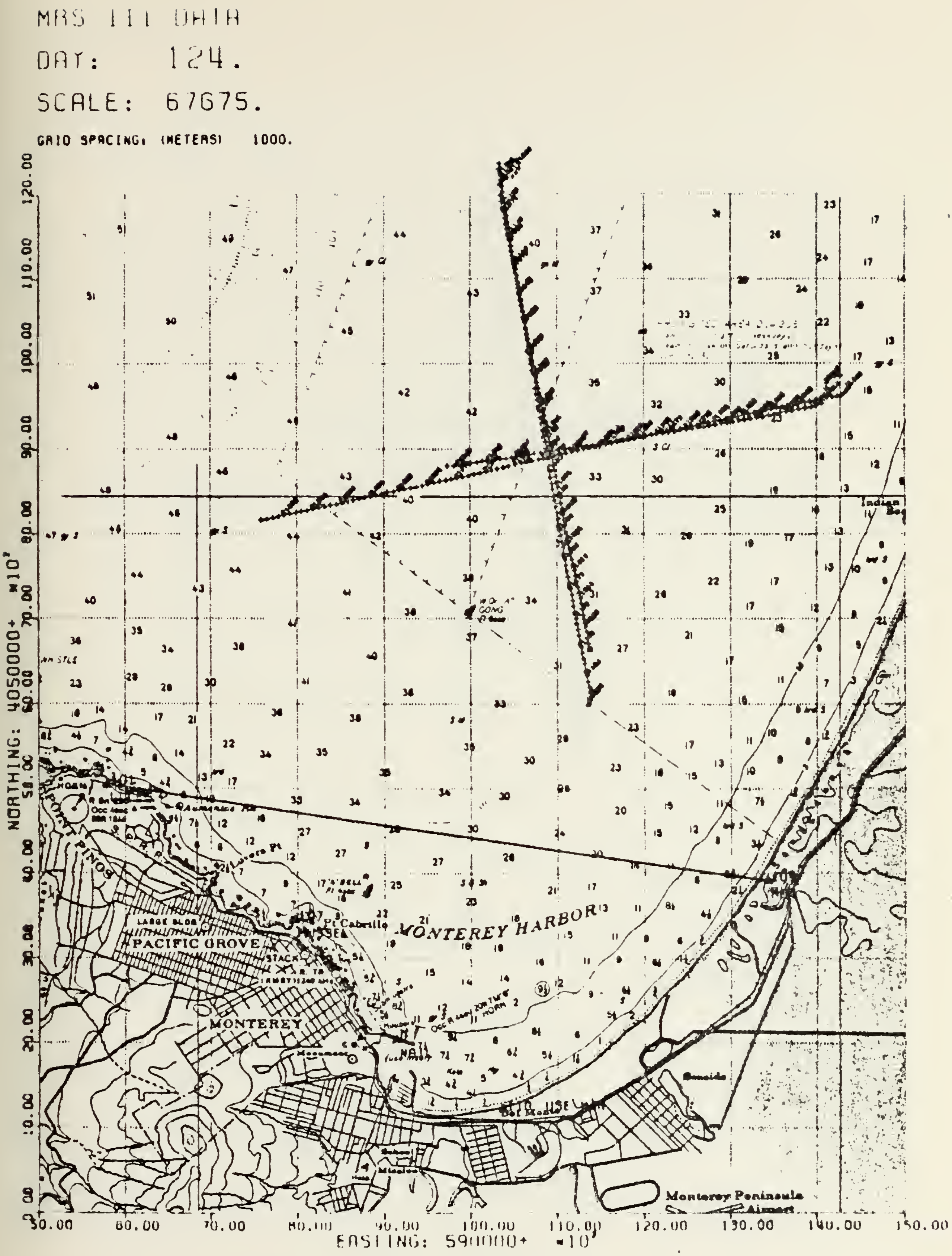


Figure 13. High Dynamic Test

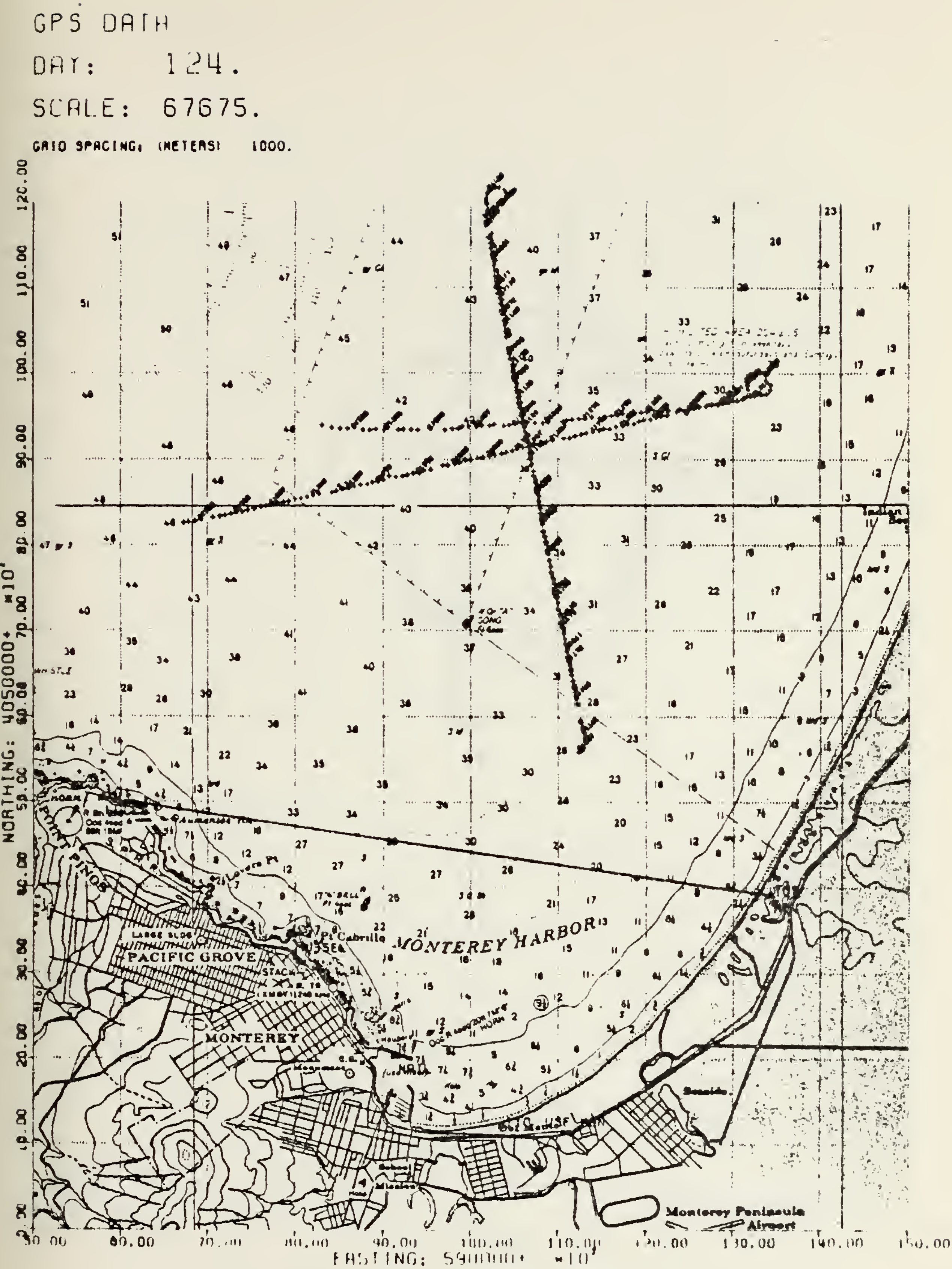


Figure 14. High Dynamic Test

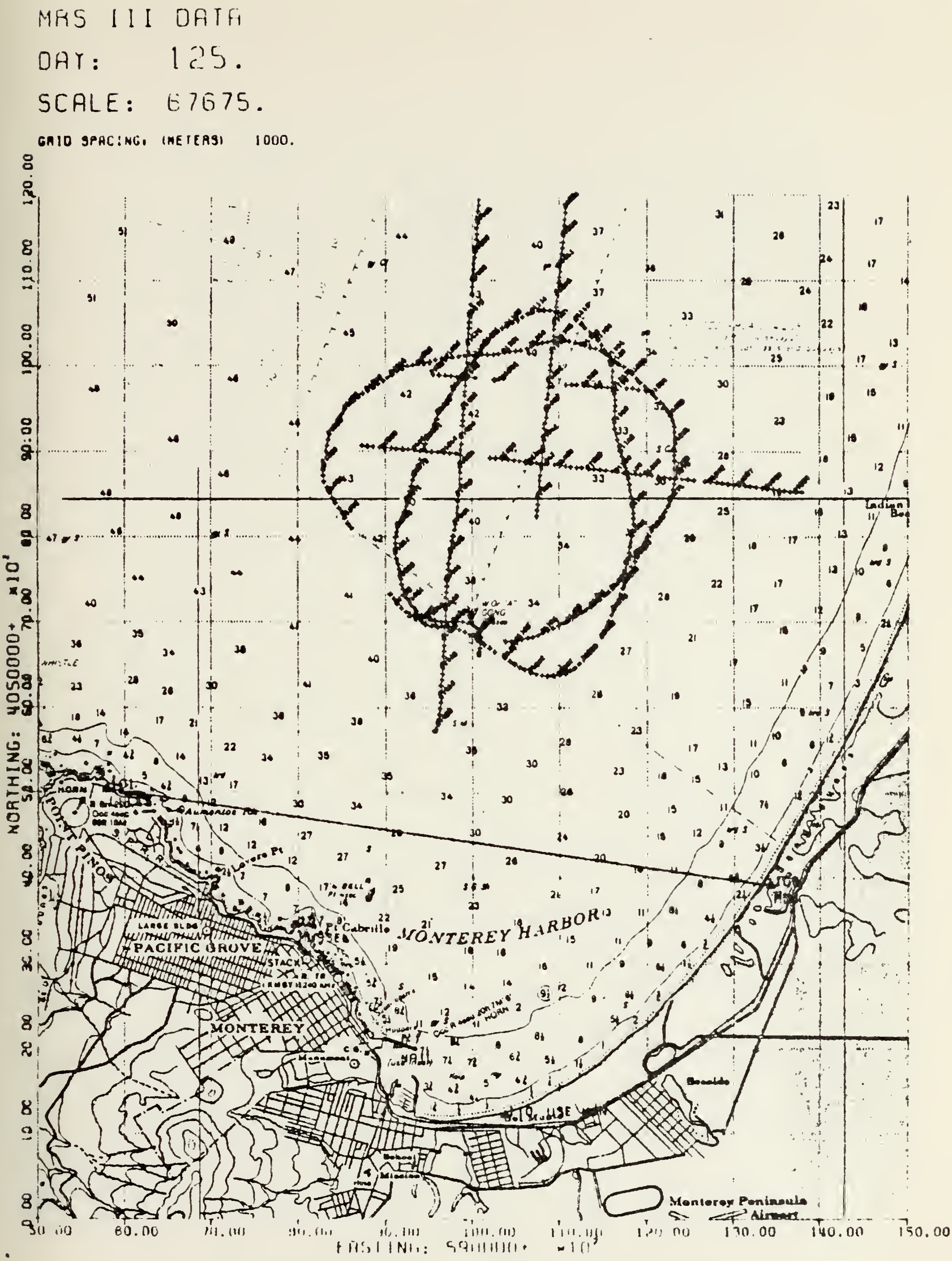


Figure 15. Circle Test

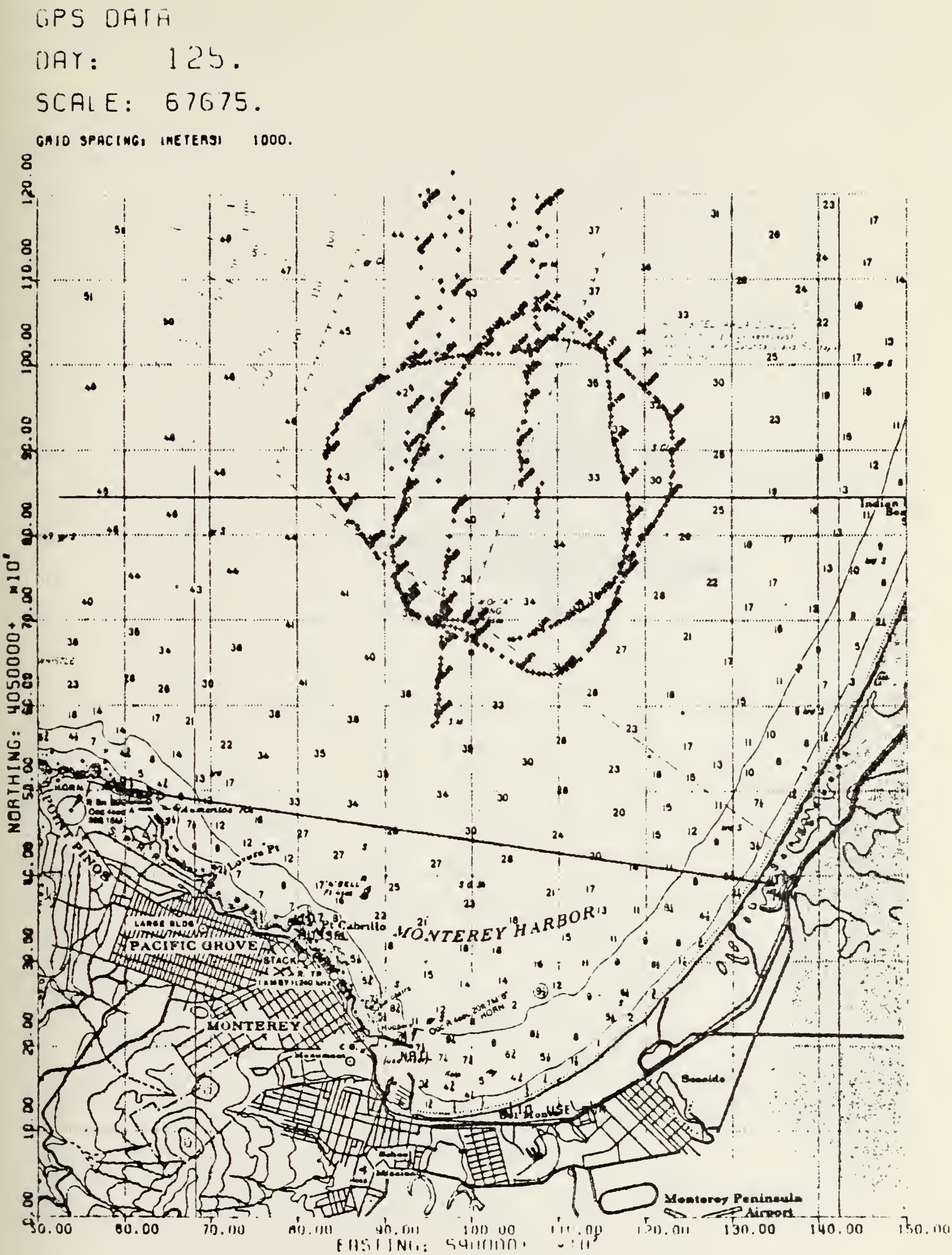


Figure 16. Circle Test

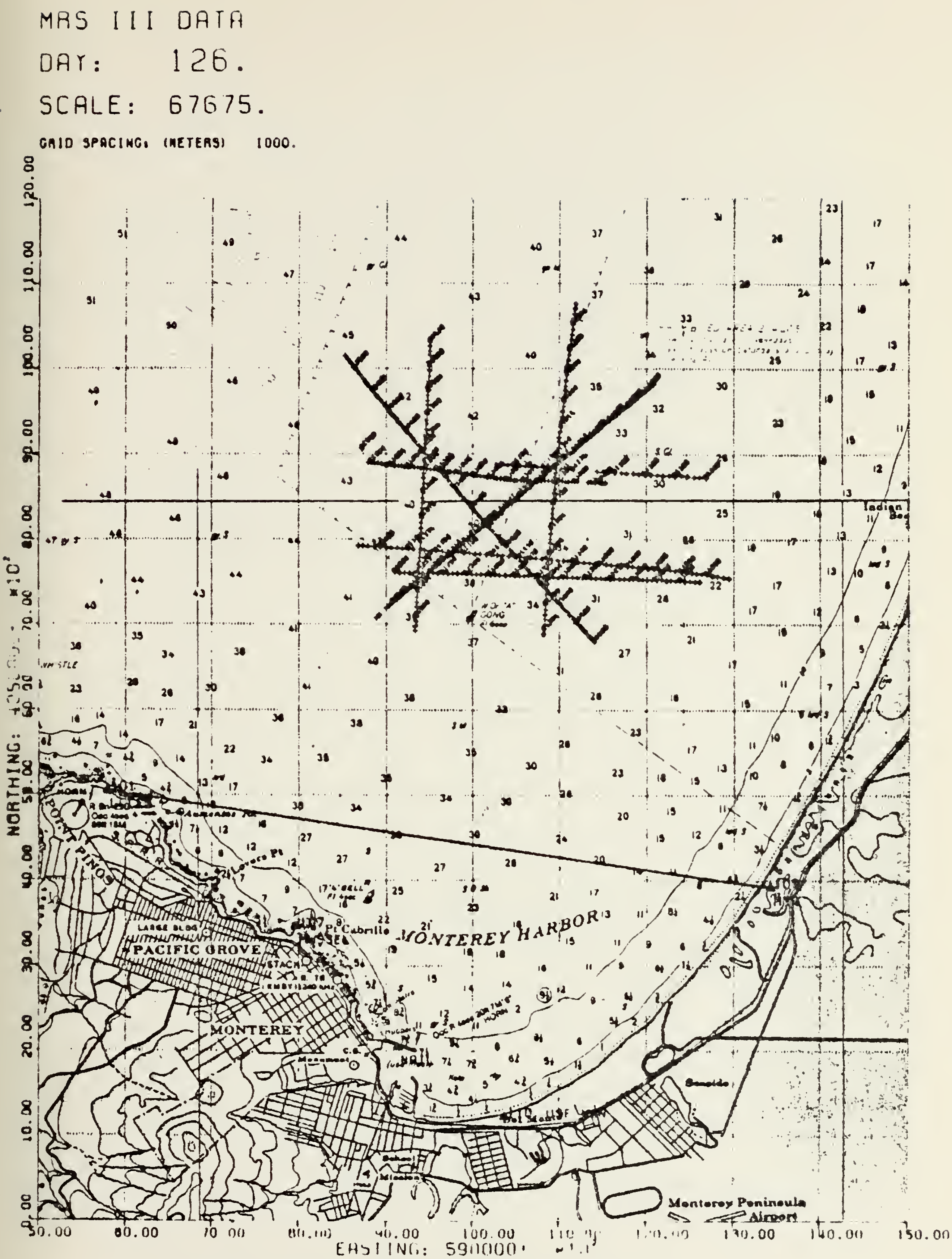


Figure 17. Nine-Knot Track Lines

GPS DATA

DAY: 126.

SCALE: 67675.

GRID SPACING: (METERS) 1000.

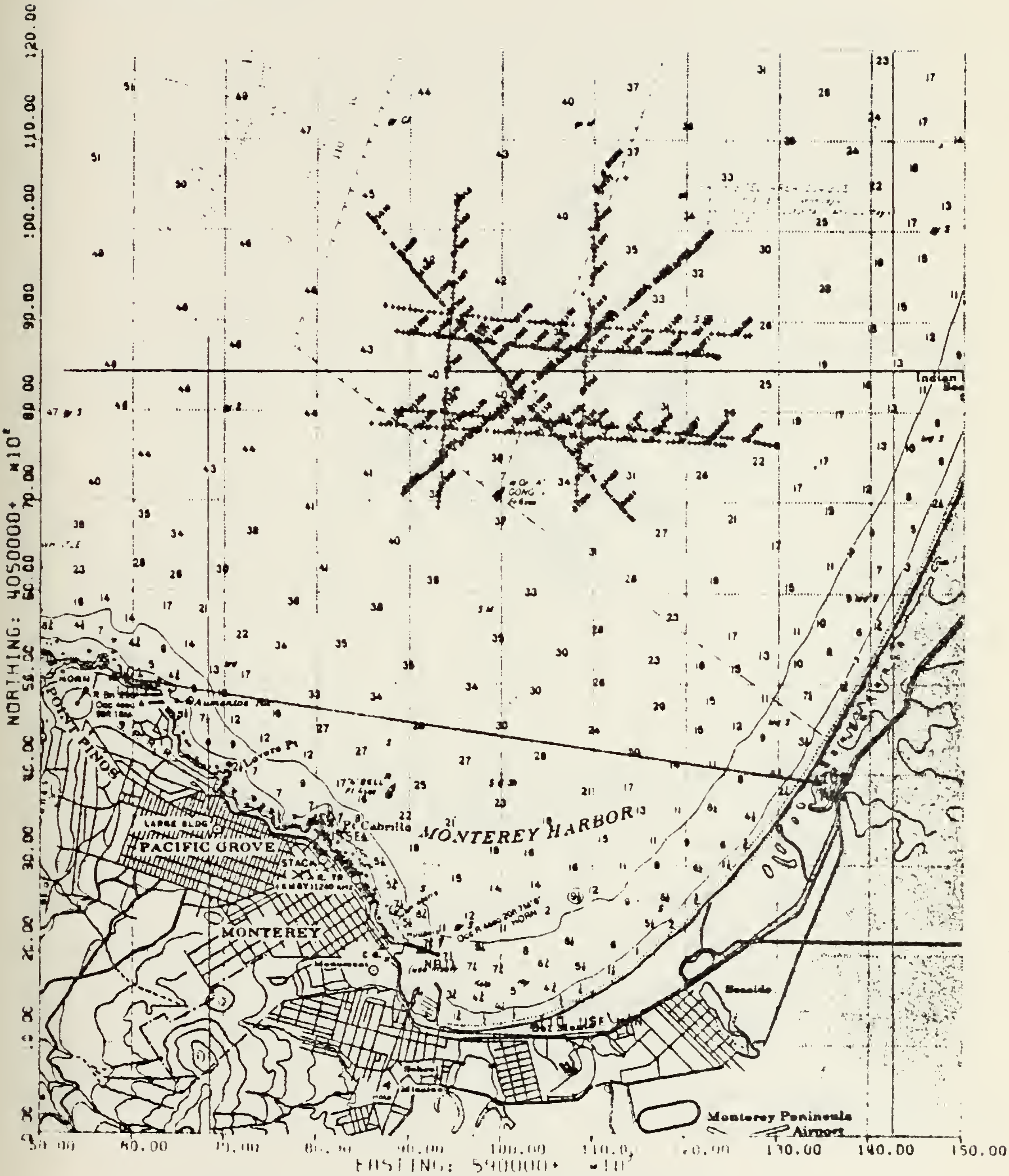


Figure 18. Nine-Knot Track Lines

MRS III DATA

DAY: 127.

SCALE: 67675.

GRID SPACING. (METERS) 1000.

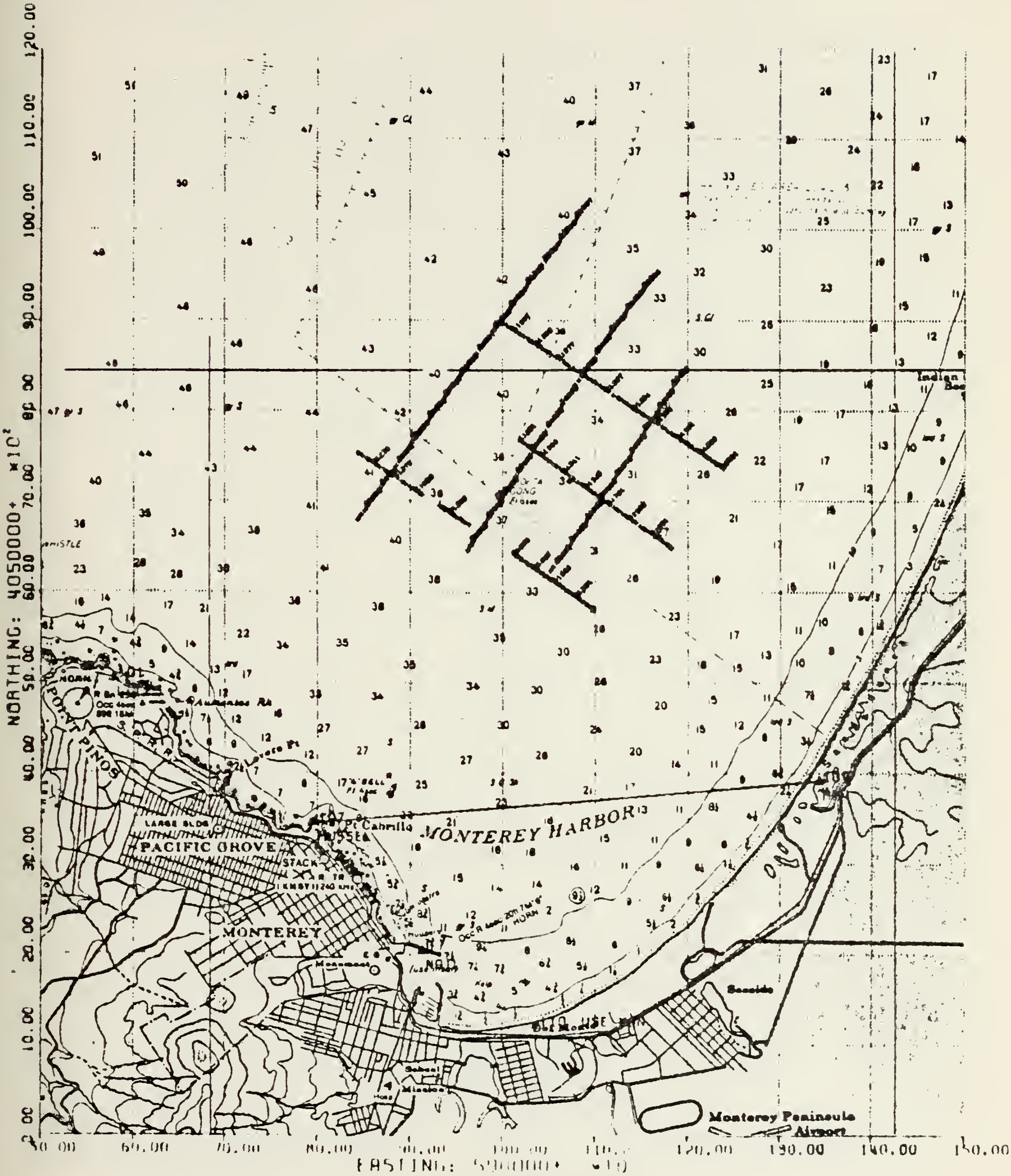


Figure 19. Five-Knot Track Lines

GPS DATA

DAY: 127.

SCALE: 67675.

GRID SPACING: (METERS) 1000.

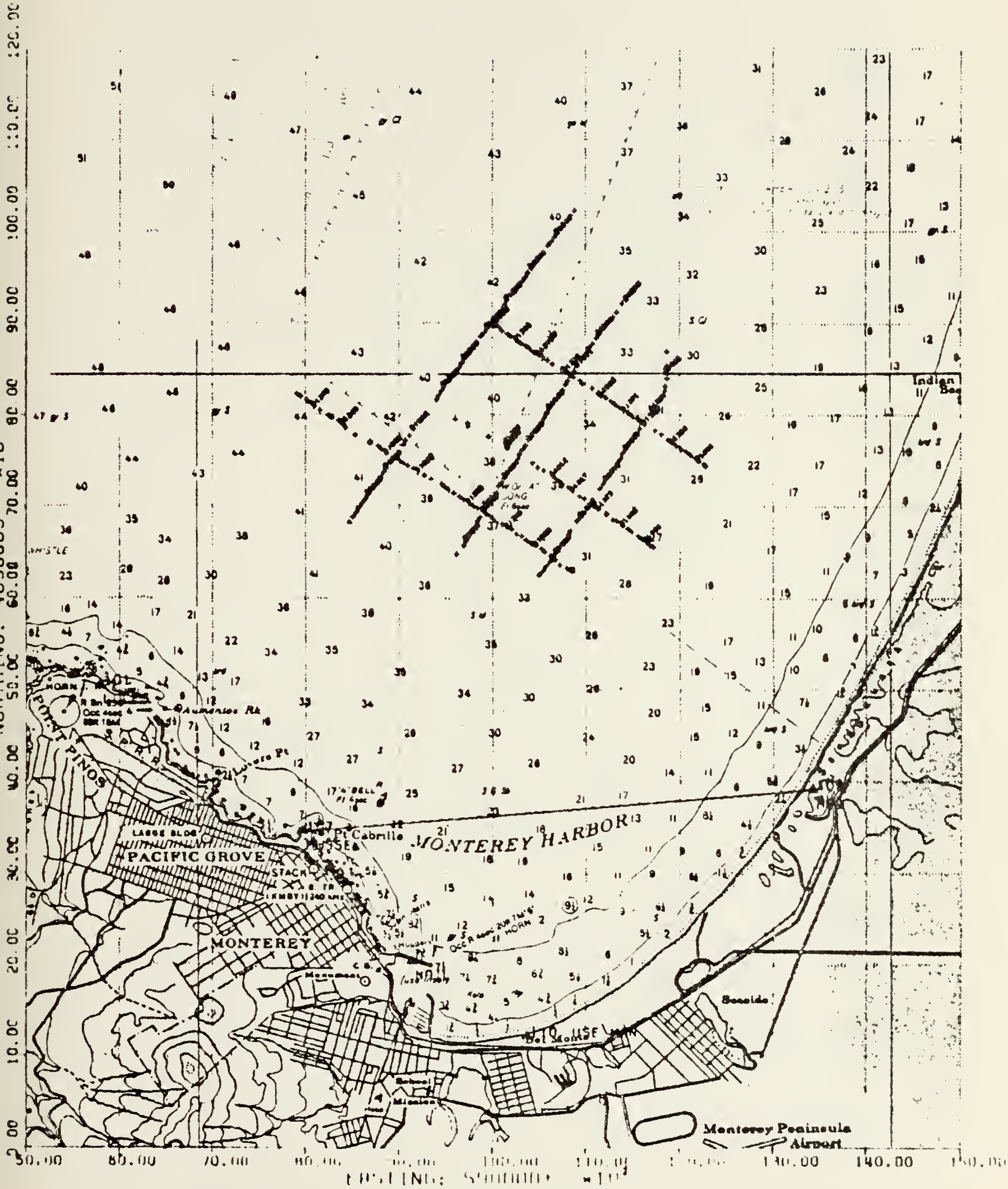


Figure 20. Five-Knot Track Lines

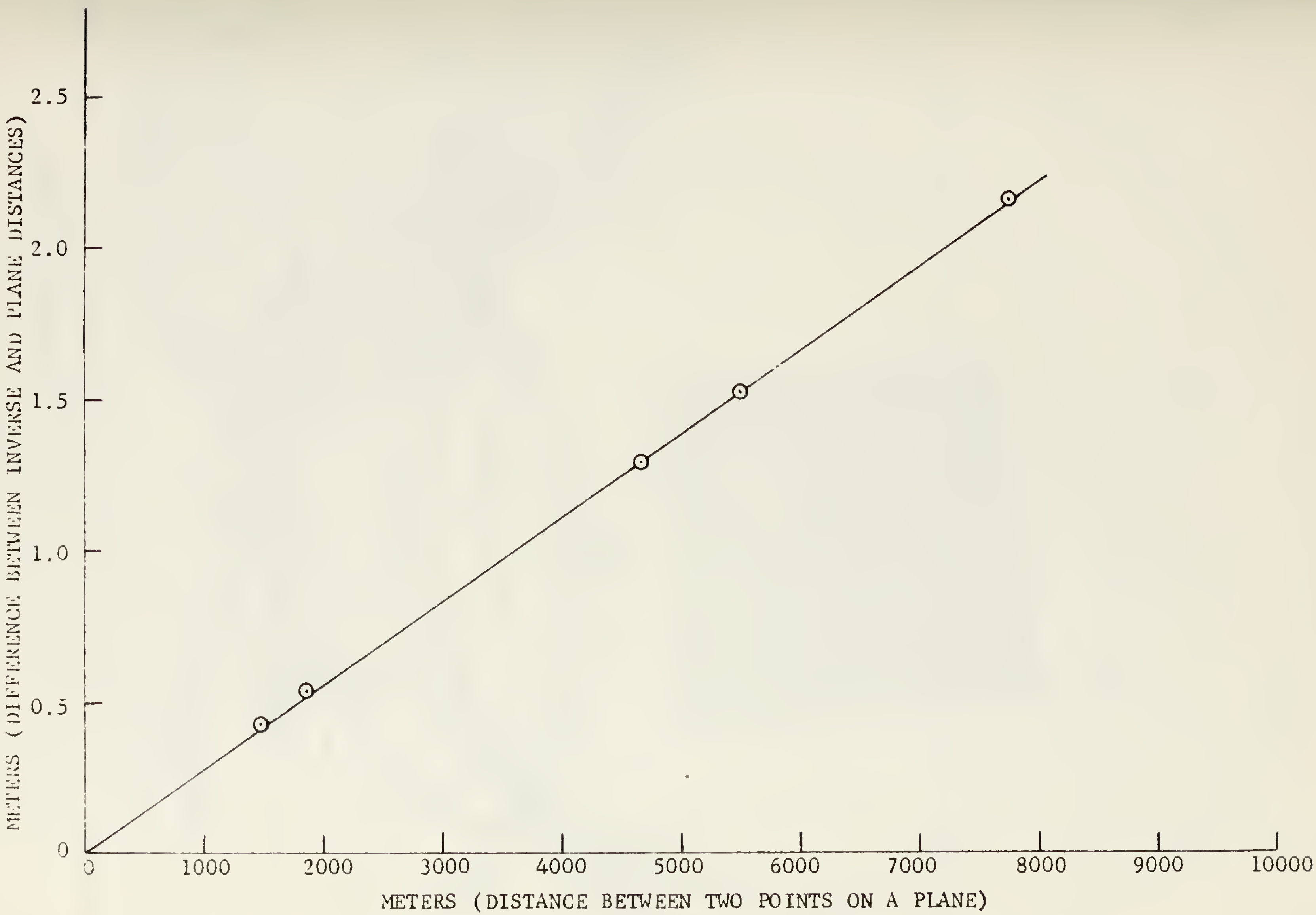


Figure 21. Plane Computations vs. Sodano Inverse Computations

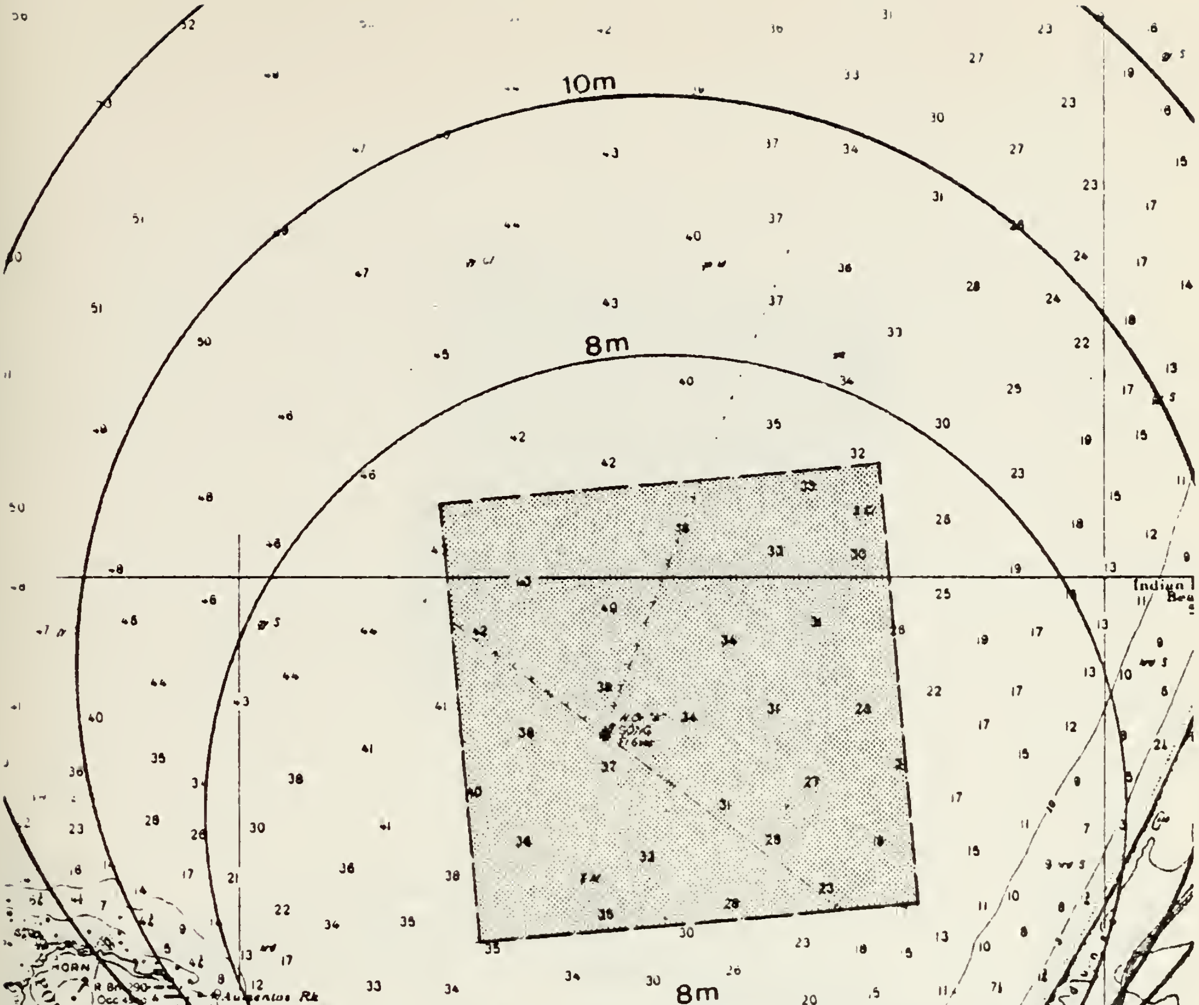


Figure 22. 2 d_{rms} Repeatability Contours (Mussel and Monterey Bay 4 Operating Area)

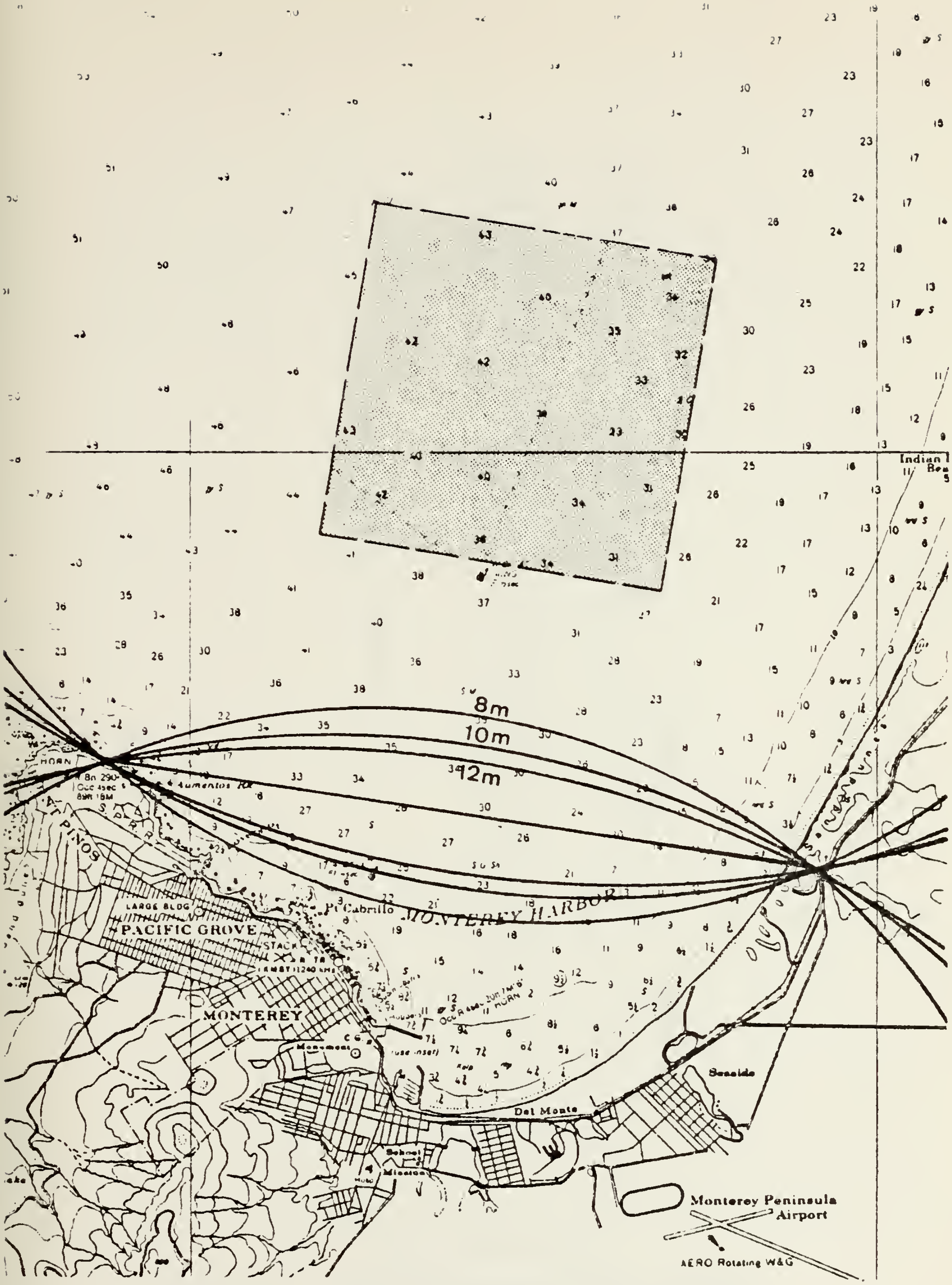


Figure 23. Two d_{rms} Repeatability Contours (Luces Pt. and Monterey Bay 4 Operating Area)

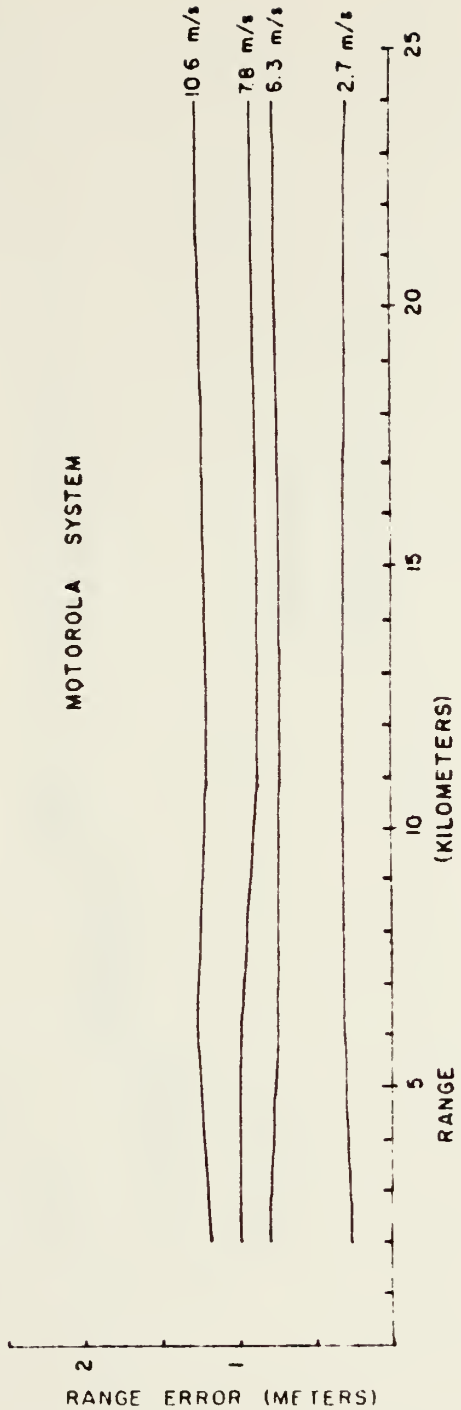


Figure 24. Speed Dependent Range Error

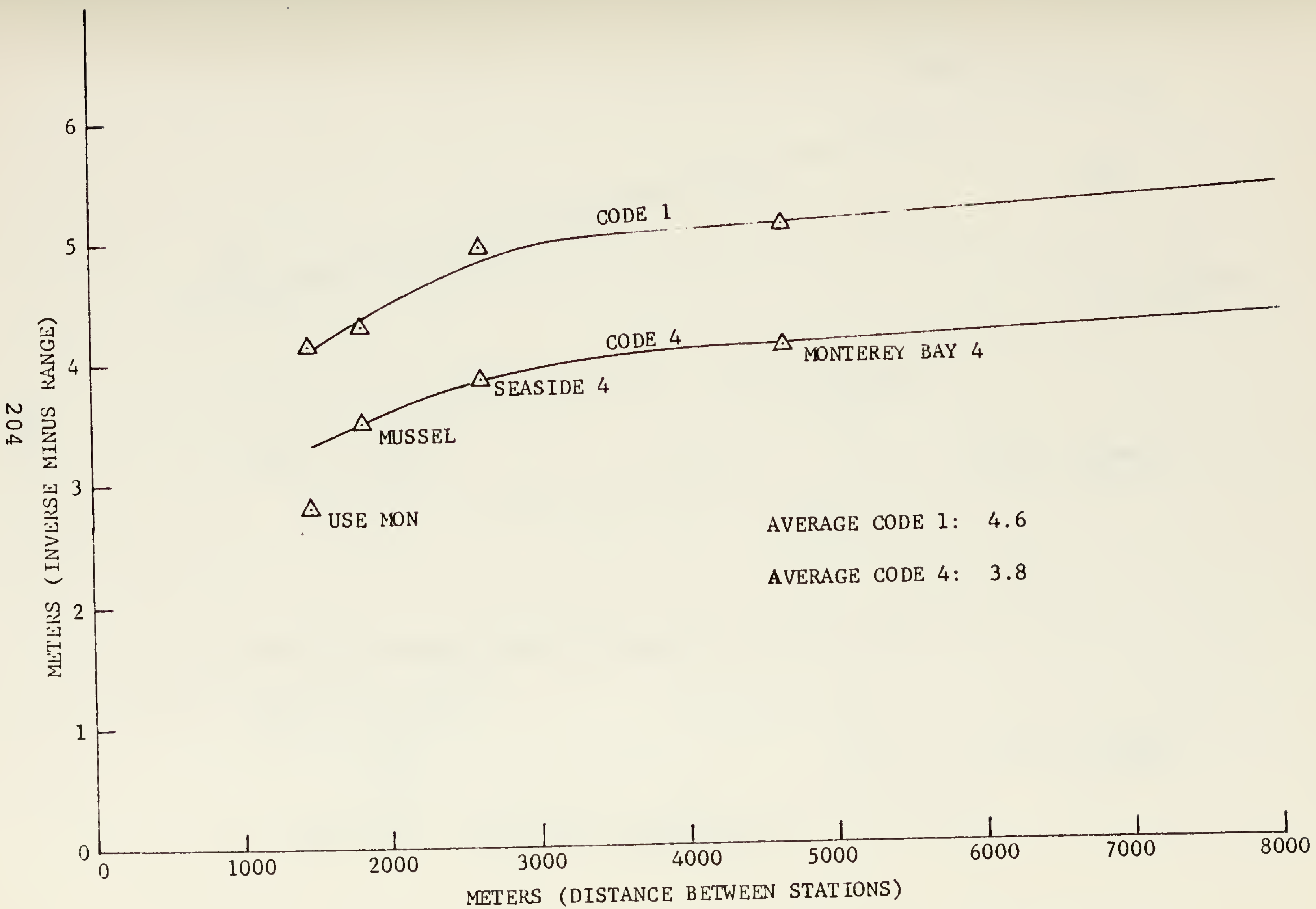
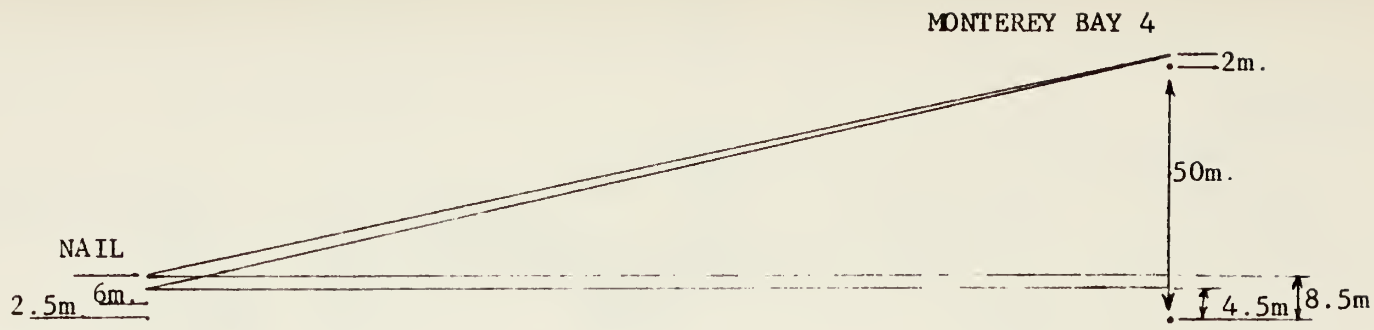


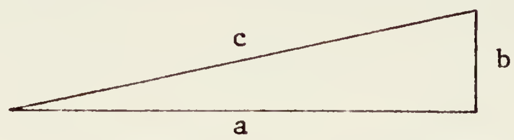
Figure 25. Range Corrections from Mini Ranger III Calibration Data



1. MRS III Control Station Elevation - 20' (6 meters)

$a = (c^2 - b^2)^{1/2}$

MAX: $a = 4674.79$
$c = 4675$
$b = 52 - 8.5$
$= 43.5$

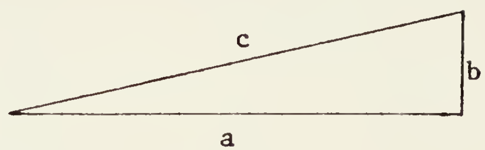


MIN: $a = 1480.4$
$c = 1481$

2. MRS III Reference Station Elevation - 6' (2 meters)

$a = (c^2 - b^2)^{1/2}$

MAX: $a = 4674.75$
$c = 4675$
$b = 52 - 4.5$
$= 47.5$



MIN: $a = 1480.3$
$c = 1481$

Figure 26. Elevation Comparison

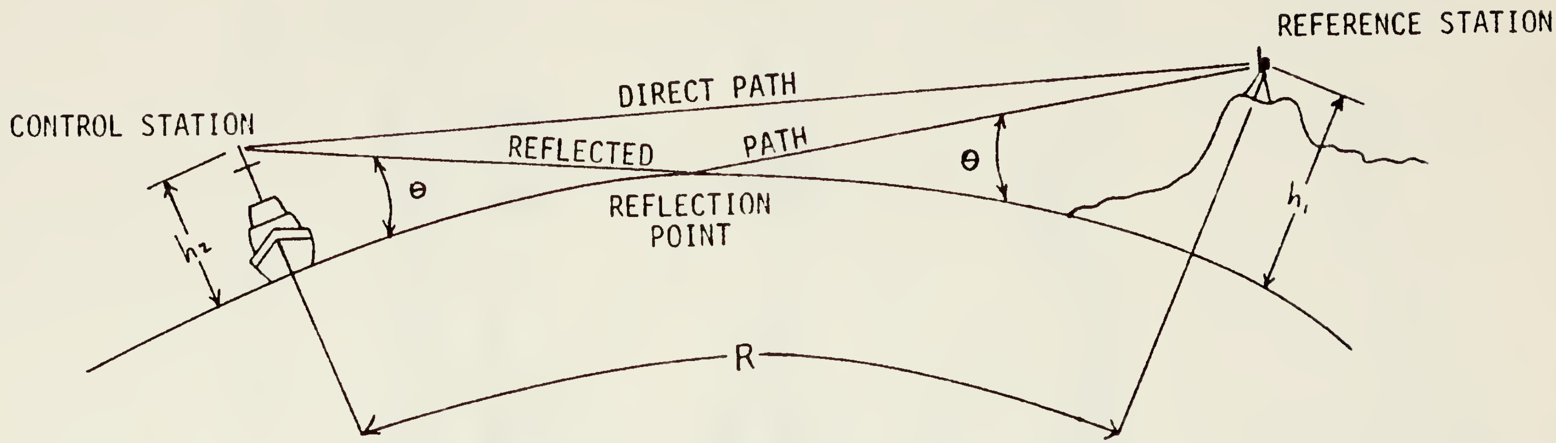
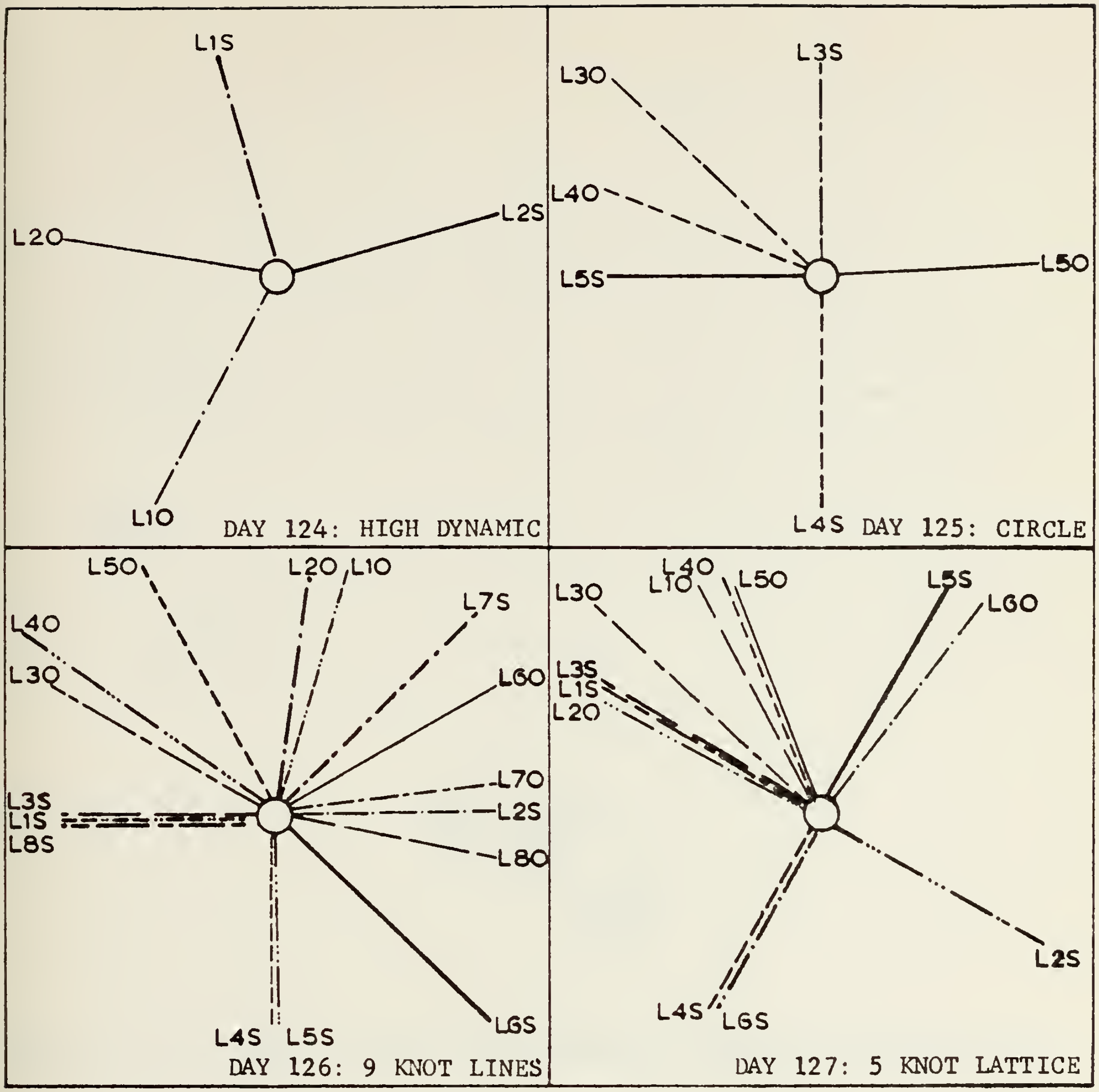


Figure 27. Multipath



O - OFFSET (FROM SOUTH)
S - SHIP TRACK (FROM NORTH)
L - LINE

Figure 28. Track Lines and Offset Azimuths

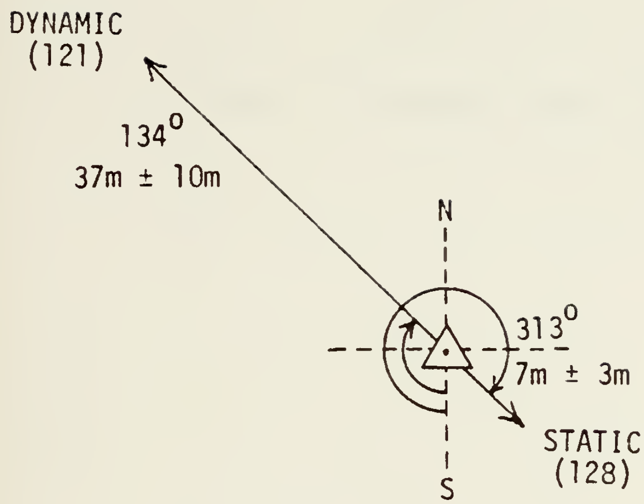


Figure 29. Offset Vectors for Days 121 and 128 (Beach Test)

Uncorrected Error Source	User Equivalent Range Error, 1 Meters	Feet
SV Clock Errors Ephemeris Errors	1.5	5.0
Atmospheric Delays	2.4-5.2	8.0-17.0
Group Delay (SV Equipment)	1.0	3.3
Multipath	1.2-2.7	4.0-9.0
Receiver Noise and Resolution Vehicle Dynamics	1.5	5.0
RSS	3.6-6.3	11.8-20.7

[Millikin, et.al., 1978]

Table I - Range Error Budget

SCALE	ACCURACY 90% LEVEL (1.645) 1.5mm	 0.5mm
1:5,000	7.5m	2.5m
1:10,000	15.0m	5.0m
1:20,000	30.0m	10.0m
1:30,000	45.0m	15.0m
1:40,000	60.0m	20.0m
1:50,000	75.0m	25.0m
1:60,000	90.0m	30.0m
1:80,000	120.0m	40.0m
1:100,000	150.0m	50.0m

Example: $10{,}000 \times 1.5\text{mm} \times 10^{-3}\text{m/mm} = 15\text{m}$

[MUNSON, 1977]

Table II - Accuracy Criteria (90%)

STATION OFFSET

Difference between WGS-72 Doppler Geographic Positions and DMA Abridged Molodensky Geographic Positions

STATION	FORWARD AZIMUTH FROM SOUTH	DISTANCE	AVERAGE AZIMUTH	AVERAGE DISTANCE
Pt. Pinos Doppler Station 10277	$309^{0}17'31''.87$	10.68m	$306^{0}02'40''.79$	9.92m
Monterey Doppler Station 10211	$302^{0}47'49''.71$	9.16m		

SHIFTED REFERENCE STATIONS

STATIONS	New ϕ	New λ	New Northing*	Δn	New Easting*	Δe
Mussel	$36^{0}37'17''.535$	$121^{0}54'15''.396$	4053447.44	5.73	597975.92	-8.06
Monterey Bay 4	$36^{0}37'30''.514$	$121^{0}50'35''.490$	4053911.44	5.73	603433.33	-8.09
Luces Point	$36^{0}38'09''.906$	$121^{0}55'42''.170$	4055036.90	5.73	595802.54	-8.06

* Coordinate Shift of Reference Stations in Meters

Table III - Coordinate Shift (Derived from Doppler Stations) Applied to Geodetic Control Stations

25 April 1980

Number of Points	Mean	σ	σ^2	Station	Code
87	1481.7	.3084	.094	USE	4
50	1480.93	.7022	.4833		1
44	4675.24	.2599	.0660	MB4	4
40	4675.43	.9472	.8747		1
43	2651.58	.3421	.1143	SS4	4
43	2650.86	.4182	.1708		1
45	1830.12	.1796	.0312	MUSSEL	4
61	1829.47	.8368	.6890		1

10 May 1980

78	4673.89	.2778	.0762	MB4	1
95	4676.05	.2440	.0589		4
104	2650.00	.2853	.0806	SS4	1
82	2651.48	.2334	.0538		4
74	1480.50	.6209	.3803	USE	1
107	1482.40	.2951	.0863		4
105	1828.79	.4267	.1803	MUSSEL	1
111	1829.75	.1394	.0193		4

Table IV - Mini Ranger III Calibration Data

DAY	LINE	AFTER UPDATE MAXIMUM	MINIMUM
121		15	14
122		14	12
123		17	12
124	L1	14	11
	L2	14	12
125	L1	11	18
	L2	13	16
	L3	353	14
	L4	38	
	L5	13621	370
	L6	252	3399
126	L1	16	12
	L2	14	13
	L3	14	11
	L4	21	13
	L5	13	
	L6	13	10
	L7	17	12
	L8	15	12
127	L1	16	11
	L2	15	
	L3	15	14
	L4	16	12
	L5	14	13
	L6	14	12

Table V - Estimated Position Error (EPE) Data from MVUE

Table VI - Track Line Data Log

Day	Line	Offset (d)	σ	Azimuth (from South) Mean α°	σ°	Time (GMT)	Number of Events	Bimodal (Low/High)	Line Direction (from North)	Velocity	Number of Satellites
121 (Beach)	L1	23	-	77	-	0605-0607	8	-		dynamic 25 m/sec	4
	L2	36	10	134 (120-140)	10	0811-0844	68	d - high right α - high right		dynamic 25 m/sec	4
122 (Pier)	L1	102	85	341 (335-350)	4	0710-0725	57	d - high left α - high right		-	2
	L2	87	12	53 (9-80)	11	0848-0912	83	d - high left α - high right		-	2
123 (Anchor)	L1	150	95	302 (290-310)	6	0738-0814	113	-		-	4
124 (High Dynamic)	L1	310	20	29.3	7	0600-0647	171	α - high left	345°	(M/S) (Knots) 4.5 8.7	3, 2
	L2	1003	150	100	5	0727-0811	166	-	075°	4.5 8.7	2
125 (Circle and Lines)	L1	31	13	100	14	0540-0620	129	-	circle left	4.5 8.7	3
	L2	30	27	292	21	0638-0718	122	-	circle right	4.5 8.7	4
	L3	297	266	132 (90-120)	19	0755-0820	74	d - high left/ low right	000°	4.5 8.7	4/5
	L4	268	166	112 (70-140)	24	0826-0839	51	d - high left	180°	4.3 8.4	5/4
	L5	21088	4674	267 (254-270)	3	0901-0920	54	d - high right	270°	4.4 8.6	4
	L6	-	-	-					090°	4.3 8.4	4
126 (Nine Knot Lines)	L1	102	5	197 (190-210)	4	0558-0615	62	-	270°	4.0 7.8	3
	L2	116	7	188 (180-195)	5	0622-0637	33	-	090°	4.0 8.6	3
	L3	363	100	121 (115-130)	4	0652-0708	62	d - high left	270°	3.7 7.2	4
	L4	54	41	125 (100-150)	11	0744-0800	60	-	180°	4.0 7.8	4
	L5	20	7	152 (120-190)	21	0809-0824	58	α - high right	000°	3.7 7.2	4
	L6	33	10	240 (210-280)	13	0844-0902	70	d - high left	135°	3.9 7.6	3
	L7	42	10	262 (250-280)	6	0617-0936	59		045°	3.5 6.8	3
	L8	55	13	282 (275-300)	7	0950-1007	63	α - high right	270°	2.7 5.2	3
127 (Five Knot Lines)	L1	671	133	152 (140-170)	8	0646-0700	36	d α - high left	300°	3.5 6.5	3/2
	L2	187	176	119 (115-125)	2	0721-0729	33	-	120°	3.7 7.2	4
	L3	50	10	133 (125-140)	5	0737-0750	44	-	300°	3.8 7.4	4
	L4	32	13	157 (140-200)	13	0800-0815	53	-	210°	3.9 7.6	4
	L5	33	22	158 (145-210)	17	0822-0833	40	-	30°	3.7 7.2	4
	L6	33	11	218 (200-225)	12	0858-0915	61	-	210°	3.8 7.4	3
128 (Beach)	L1	49	65	317 (0-360)	25	0631-0705	70	-	-	static 0	4
	L2	7	3	313 (0-360)	29	0735-0805	49	d - high left α - high left	-	static 0	4

A.	Geodetic Control	<.4m
B.	Position Error[1] (due to coordinate shift)	4m
C.	Inverse[2] (Ellipsoid vs. Plane Computation)	.02m
D.	GDOP	4m
E.	Range Correction	3m
F.	Meteorological	.06m
G.	Station Elevation	.1m
H.	Timing[3]	0 - 4 m
I.	MRS III Positioning	.5m
J.	Antenna Motion	0 - 2 m

1 - Based on offset between Doppler station and abridged Molodensky Formulas
2 - Maximum at distances less than 1000 meters
3 - Depends on trends in data

TOTAL ERROR

$$E_{T_{min}} = e_A + e_B + e_C + e_D + e_E + e_F + e_G + e_H + e_I + e_J$$

$$= \sqrt{.4^2 + 4^2 + .02^2 + 4^2 + 3^2 + .06^2 + .1^2 + 0 + .5^2 + 0}$$

with e_H (timing) = 0 and e_J (antenna motion) = 0

= 6.4m

$$E_{T_{max}} = \sqrt{.4^2 + 4^2 + .02^2 + 4^2 + 3^2 + .06^2 + .1^2 + 4^2 + .5^2 + 2^2}$$

with e_H = 4m and e_J = 2m

= 7.8m

$E_{T_{avg}}$ = 7m

RAW DATA: 38 meters with 11 meter standard deviation

CORRECTED: 38 - 7 = 31 meters

Table VII - Mini Ranger III Position Error

DATE	TIME	RANGE (METERS) STATION TO R/V ACANIA MB4 (CODE 1)	MUSSELL (CODE4)	NORTHING	EASTING
4/24	Day	4676	1833	4052043	599139
4/30	Night	4676	1831	4052044	599139
5/6	Night	4677	1832	4052044	599138

Table VIII - Pierside Range and UTM Values

STATION NAME	LATITUDE: Entered	Returned	$\Delta\phi$	LONGITUDE: Entered	Returned	$\Delta\lambda$
LUCES	36°38'10".1	09".9	".2	121°55'42".5	42".4	".1
MONTEREY BAY 4	36°37'30".7	30".5	".2	121°50'35".8	35".6	".2
MONTEREY COUNTY DISK	36°36'31".7	31".6	".1	121°53'28".1	28".0	".1
MUSSEL	36°37'17".7	17".5	".2	121°54'15".7	15".6	".1
NAIL	36°36'31".5	31".4	".1	121°53'29".2	29".1	".1
USE MONUMENT	36°36'04".3	04".1	".2	121°52'40".0	39".9	".1

Azimuth; entered to return from south: between 315° and 333°.

1 minute = 60 seconds = 1 n.m. = 1852 meters

1 second = $\frac{1852\text{m}}{60\text{ sec}}$ = 30.87 meters

.1 second = 3 meters

$$d = \sqrt{\Delta\phi^2 + \Delta\lambda^2}$$
$$= \sqrt{6^2 + 6^2} = 8.5 \text{ meters}$$
$$= \sqrt{6^2 + 3^2} = 6.7 \text{ meters}$$
$$= \sqrt{3^2 + 3^2} = 4.2 \text{ meters}$$
$$d_{mean} = 6.2 \text{ meters}$$

Mean Offset: direction 324°
magnitude 6.2 meters
(Average from south)

Table IX - WGS-72 Geodetic Positions (Waypoints) Extend into MVUE vs. Returned Values

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